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COMPARATIVE PERFORMANCE OF STRUCTURAL LAYERS IN PAVEMENT SYSTEMS

VOLUME II

Analysis of Test Section Data and Presentation of Design and Construction Procedures

U. S. Army Engineer Waterways Experiment Station
Soils and Pavements Laboratory
P. O. Box 631, Vicksburg, Miss. 39180

APRIL 1977
FINAL REPORT

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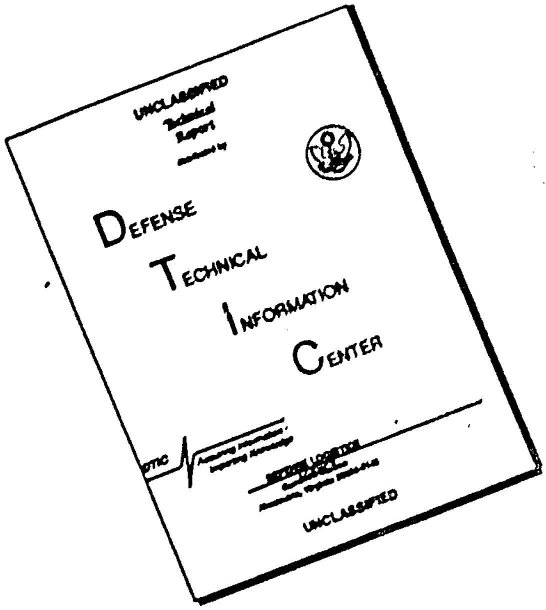

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16. Abstract

Comparative performance analyses of full-scale pavement test sections indicated that reductions in conventional flexible and rigid pavement thickness requirements are warranted when high-quality stabilized layers are incorporated in the pavement structure. Based on the findings in the analyses, design procedures for airport pavement systems incorporating certain types of stabilized layers were developed. Construction procedures for stabilized layers were developed based on field operations. This volume of the report summarizes pertinent data from the test sections, describes the analyses, and presents the design and construction procedures. Volume I of the report describes in detail the design, construction, and behavior under traffic of test sections specially designed for this study. Volume III describes analysis of membrane-encapsulated soil layers (MESL) and presents design and construction procedures for airport pavements incorporating MESL. Volume IV describes the performance and analysis of insulating layers in pavement test sections.

10 James P./Sale, R.L./Hutchinson, H.H./Ulery
D.M./Ladd W.R./Barker

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PREFACE

The investigation reported herein was jointly sponsored by the Office, Chief of Engineers, U. S. Army, as a part of the Military Engineering Design and Expedient Construction Criteria Program and the Military Construction Short-Range Airfield Pavement Research Program and by the Federal Aviation Administration as a part of Inter-Agency Agreement FA71WAI-218, "Development of Airport Pavement Criteria." The investigation was conducted from March 1972 to July 1976.

The project was conducted under the general supervision of Mr. James P. Sale, Chief, Soils and Pavements Laboratory (S&PL), U. S. Army Engineer Waterways Experiment Station (WES). Personnel of the S&PL involved in the development and presentation of the design and construction procedures presented in this report were Messrs. R. L. Hutchinson, H. H. Ulery, Jr., and D. M. Ladd; Drs. W. R. Barker, G. M. Hammitt II, and Y. T. Chou; and Mr. C. L. Rone.

During this project and the preparation and publication of this report, Directors of WES were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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METRIC CONVERSION FACTORS

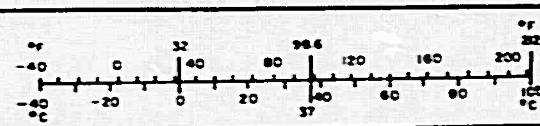
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



INTRODUCTION

BACKGROUND

For many years soil stabilization has been used in pavements primarily as an expediency to construction or to upgrade an otherwise marginal quality material. It has generally been recognized that the stabilized soil, because of its inherent strength or stability, improves the overall structure and provides better performance or increases the life of the pavement. However, because of the lack of a methodology to assess this increased performance or life, little structural advantage (i.e., thickness reduction) has been taken when stabilized soil layers have been used. The absence of design methodology is generally considered to result from the lack of factual data regarding the long-time performance of pavements incorporating stabilized soil layers. This lack of performance data is not surprising when the large number of influencing parameters are considered (i.e., type of stabilizer, quantity of stabilizer, type of material stabilized, thickness of material stabilized, etc.).

Soil stabilization has been used more extensively in highway pavement construction than for airports. Several design agencies have generated equivalency factors which equate the thickness of a stabilized soil layer to an equivalent thickness of an unbound soil layer. These equivalency factors have been empirically developed from performance data, and are applicable to the conditions from which developed, but can also be extended to other conditions. Therefore, equivalency factors can serve a useful purpose in allowing stabilized layers to be used in pavement design.

PURPOSE

The purpose of this report is to present an analysis of available data on the performance of stabilized soil layers in airport pavement sections and based upon that analysis to present recommended thickness design procedures for the use of such layers in both flexible and rigid pavements. In addition, recommended construction practices gained from

experience in test section construction and actual field observations are presented.

SCOPE

Tests have been conducted[1-4] on full-scale test sections containing stabilized soil layers within rigid and flexible pavement structures. These test sections contained different soil types stabilized with lime, cement, bitumen, or a combination of lime, cement, and fly ash. The sections were trafficked under different simulated aircraft loadings. As a result of these tests, sufficient data were available to develop equivalency factors for application to the design of flexible pavements containing stabilized layers and to develop a procedure for the design of rigid pavements containing stabilized soil layers.

APPROACH

Several approaches were considered for the analysis of the available performance data. These range from the development of equivalency factors to the use of theoretical analyses. Invariably it was found that there was an insufficient amount of data available to develop an empirical relationship that would have an acceptable confidence level or to verify an analytical procedure based upon an acceptable theory. Nonetheless, the results of the analysis are presented along with recommended design and construction guides for stabilized soil layers in airport pavements.

A theoretical method was considered for the analysis of the flexible pavement data but was found at this time not to be developed to the extent needed to provide a design procedure compatible with other procedures. During the testing phase of this study, the theoretical procedures were used to select the loads to be applied to one of the test lanes and this work is reported in Appendix A. In this appendix, comparisons are presented between two theoretically based procedures which were considered in the analysis of available data. However, the main thrust of the analysis of the flexible pavement performance data was to develop equivalency factors for use with

the current design procedure. These equivalency factors relate the thickness of a stabilized soil layer to an equivalent thickness of an unbound subbase or base course material. Unconfined compression strength (UCS) tests were conducted on several of the stabilized soils and the equivalency factors related to the UCS. This allows the selection of an equivalency factor based upon the UCS of the stabilized soil.

Performance data from only four full-scale accelerated traffic test items are available for the development of design methodology for stabilized layers in rigid pavements. The available data were analyzed as slabs on grade, as partially bonded rigid overlays, and using the Portland Cement Association (PCA) adjusted radius of relative stiffness method. The overlay equations gave the best results and were selected for use in design.

Much work is under way by various research agencies to develop theoretically based design procedures for airport pavements which when finalized will permit the proper assessment of structural benefits to soil stabilized layers. Until that time, or until more factual performance data are available for airport pavements, the use of the procedures outlined herein, if used with discretion and sound engineering judgment, should result in adequate designs giving structural credit to stabilized soil layers.

PREVIOUS STUDIES

Results from tests conducted prior to this study and a preliminary analysis of data produced from this study resulted in the development of equivalency factors based upon a total thickness concept. These factors were developed by determining the thickness of conventional flexible pavement which would perform (produce same number of coverages to failure) in the same manner as the stabilized pavement. These two thicknesses were related and an equivalency factor produced. This was accomplished for each test item and, as a result, a table of equivalency factors was developed. These factors were used in References 5 and 6. Further analysis of the test data showed that a more reasonable analysis was to study the data in terms of layer thickness ratios rather than total thickness ratios. Therefore, this report presents the results of an analysis directed at determining equivalency factors based upon layer thicknesses.

Procedures for selecting the type of stabilizing agent and the percent of stabilizer have been developed and reported in References 5 and 7.

TEST SECTIONS AND DATA

Results of three test sections were used to obtain data for this analysis. Results from the test section that was constructed as a part of this study are reported in Reference 1. A plan and cross section of this test section are shown in Figure 1. The other test sections were constructed and trafficked under related projects. The results of these test sections were extracted from References 2 and 3 and a plan and cross section of each of these test sections are shown in Figures 2 and 3. The data from these three test sections that were used in this analysis are shown in Table 1.

CONVENTIONAL FLEXIBLE PAVEMENT TEST ITEMS

Figure 1 shows item 5 to be a conventional flexible pavement

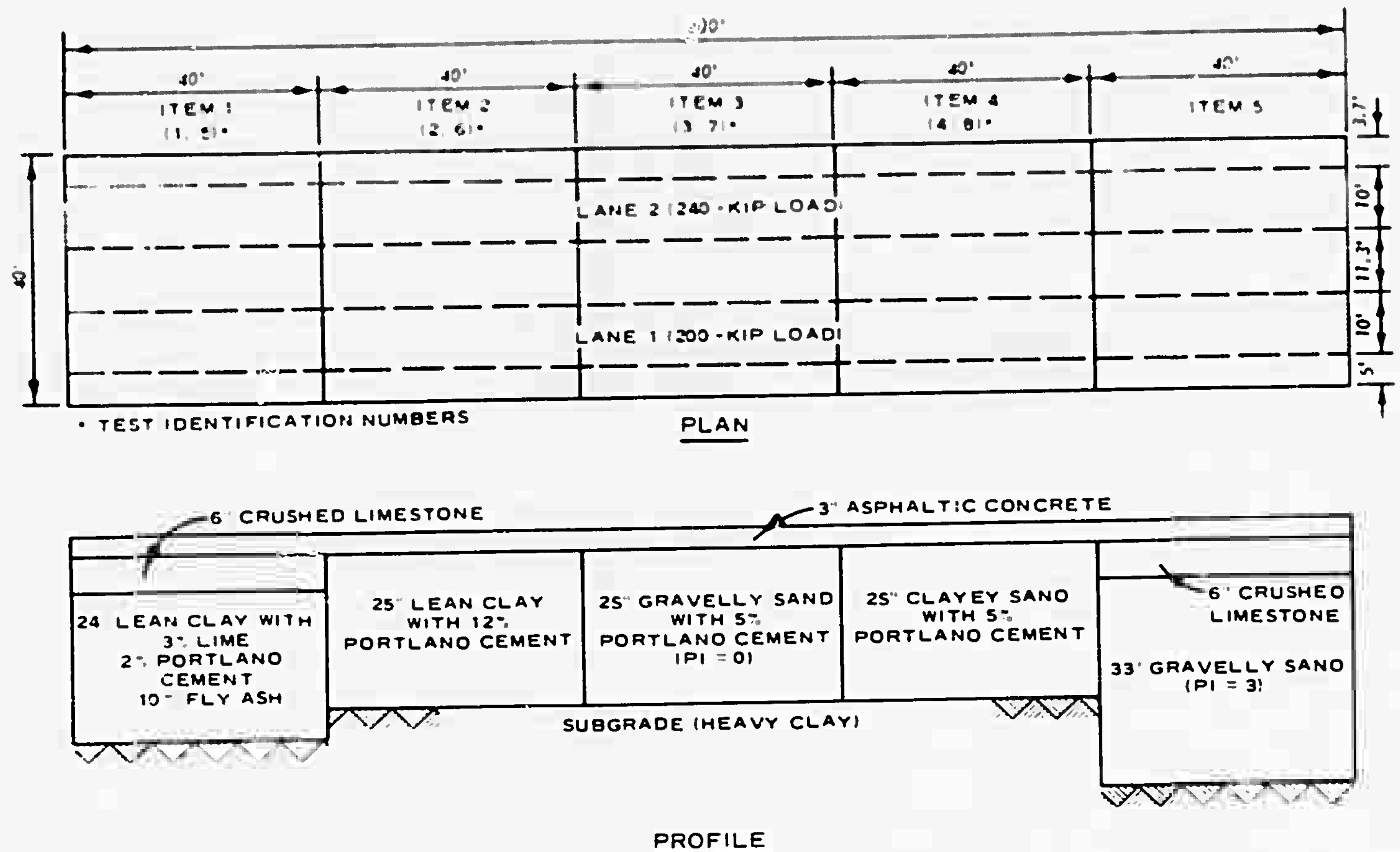


Figure 1. Layout of flexible pavement test section (after Reference 1)

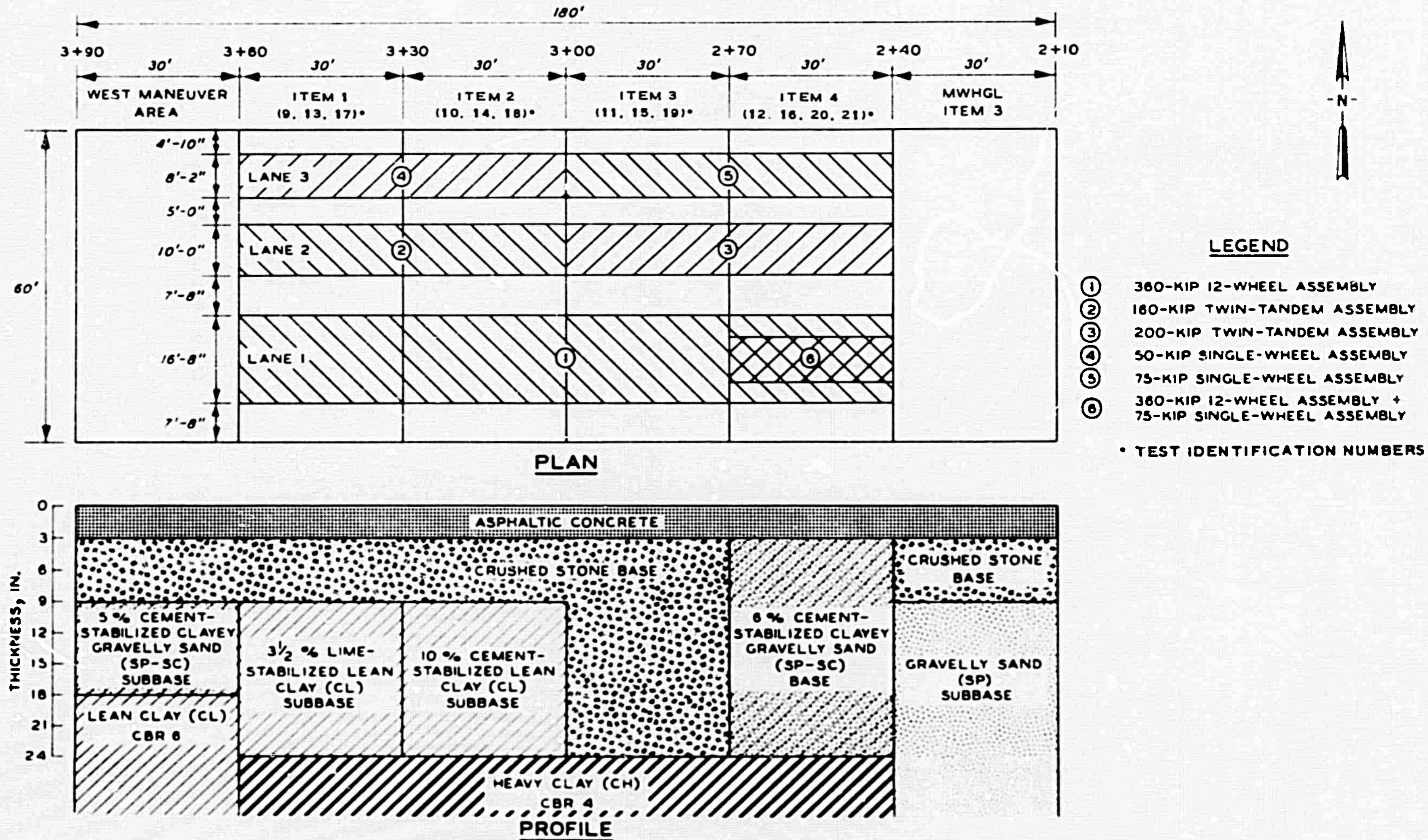


Figure 2. Layout of flexible pavement test section (after Reference 2)

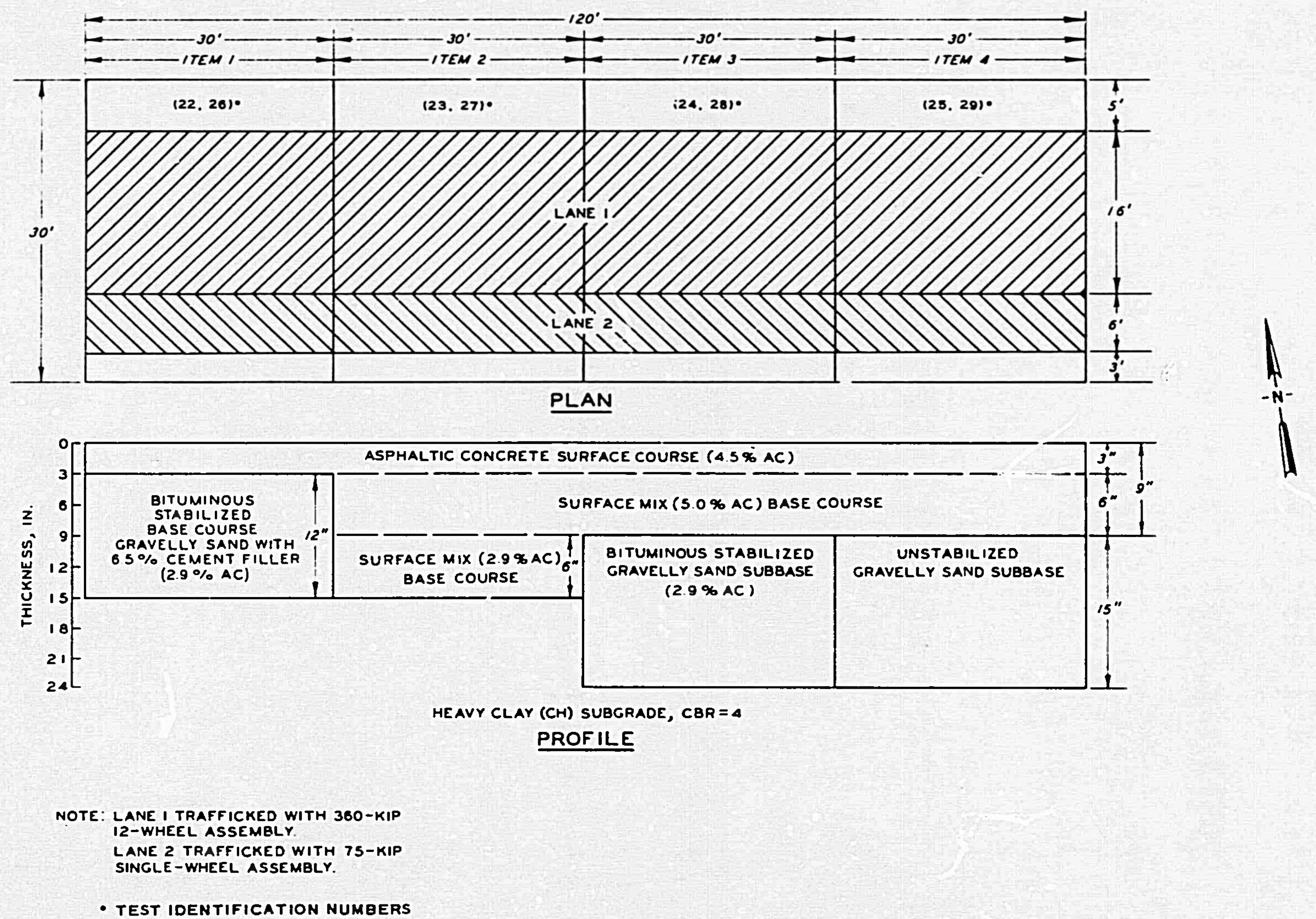


Figure 3. Layout of flexible pavement test section (after Reference 3)

Table 1

Summary of Test Data for Stabilized Soil Layers in Flexible Pavement

Test Item Identification Number	Data Source: Reference	Data Source: Test Lane	Data Source: Test Item	Test Gear Arrangement	Gear Load kips	Thickness of Surface Course, in.	Base Course: Thickness in.	Base Course: Material	Base Course: Stabilizing Agent	Subbase Course: Thickness in.	Subbase Course: Material	Subbase Course: Stabilizing Agent	Total Test Section Thickness, in.	Subgrade CBR	Coverages to Failure	Unconfined Compressive Strength psi
1	1	1	1	Twin-Tandem	200	3	6	Crushed Stone	-	24	Lean Clay	Lime, Cement, Fly Ash	33	5.6	3,660	189.8
2	1	1	2	Twin-Tandem	200	[illegible]	25	Lean Clay	Cement	-	-	-	28	5.4	3,660	613.9
3	1	1	3	Twin-Tandem	200	3	25	Gravelly Sand	Cement	-	-	-	28	3.8	7,820	782.4
4	1	1	4	Twin-Tandem	200	3	25	Clayey Sand	Cement	-	-	-	28	4.9	1,380	—
5	1	2	1	Twin-Tandem	240	3	6	Crushed Stone	-	24	Lean Clay	Lime, Cement, Fly Ash	33	4.4	600	189.8
6	1	2	2	Twin-Tandem	240	3	25	Lean Clay	Cement	-	-	-	28	4.0	340	613.9
7	1	2	3	Twin-Tandem	240	3	25	Gravelly Sand	Cement	-	-	-	28	3.2	620	782.4
8	1	2	4	Twin-Tandem	240	3	25	Clayey Sand	Cement	-	-	-	28	5.2	120	—
9	2	1	1	12-Wheel	360	3	6	Crushed Stone	-	15	Lean Clay	Lime	24	5.0	198	219.5
10	2	1	2	12-Wheel	360	3	6	Crushed Stone	-	15	Lean Clay	Cement	24	4.3	1,200	714.0
11	2	1	3	12-Wheel	360	3	21	Crushed Stone	-	-	-	-	24	4.3	5,000	—
12	2	1	4	12-Wheel	360	3	21	Clayey, Gravelly Sand	Cement	-	-	-	24	4.2	10,406*	1129.3
13	2	2	1	Twin-Tandem	160	3	6	Crushed Stone	-	15	Lean Clay	Lime	24	5.0	140	219.5
14	2	2	2	Twin-Tandem	160	3	6	Crushed Stone	-	15	Lean Clay	Cement	24	4.3	1,000	714.0
15	2	2	3	Twin-Tandem	200	3	21	Crushed Stone	-	-	-	-	24	4.3	890	—
16	2	2	4	Twin-Tandem	200	3	21	Clayey, Gravelly Sand	Cement	-	-	-	24	4.2	1,810	1129.3
17	2	3	1	Single	50	3	6	Crushed Stone	-	15	Lean Clay	Lime	24	5.0	40	219.5
18	2	3	2	Single	50	3	6	Crushed Stone	-	15	Lean Clay	Cement	24	4.3	90	714.0
19	2	3	3	Single	75	3	21	Crushed Stone	-	-	-	-	24	4.3	50	—
20	2	3	4	Single	75	3	21	Clayey, Gravelly Sand	Cement	-	-	-	24	4.2	120	1129.3
21	2	1	4	12-Wheel & Single	360 & 75	3	21	Clayey, Gravelly Sand	Cement	-	-	-	24	4.2	200**	—
22	3	1	1	12-Wheel	360	3	12	AC	Asphalt	-	-	-	15	4.4	98	—
23	3	1	2	12-Wheel	360	3	6	AC	Asphalt	6	AC	Bitumen	15	4.2	425	—
24	3	1	3	12-Wheel	360	3	6	AC	Asphalt	15	Gravelly Sand	Bitumen	24	4.9		—
25	3	1	4	12-Wheel	360	3	6	AC	Asphalt	15	Gravelly Sand	-	24	3.8	734	—
26	3	2	1	Single	75	3	12	AC	Asphalt	-	-	-	15	4.5	6	—
27	3	2	2	Single	75	3	6	AC	Asphalt	6	AC	Bitumen	15	4.0	8	—
28	3	2	3	Single	75	3	6	AC	Asphalt	15	Gravelly Sand	Bitumen	24	4.9	90	—
29	3	2	4	Single	75	3	6	AC	Asphalt	15	Gravelly Sand	-	24	4.1	12	—

* No failure at this load.
** Coverages of 75 kip single-wheel load only.

test item which was trafficked with a 200-kip and 240-kip twin-tandem load. This test item sustained 2500 coverages of the 200-kip load on lane 1 and 340 coverages of the 240-kip load on lane 2. Using existing criteria, 2500 coverages of the 200-kip load would require 45 in. of flexible pavement and 340 coverages of the 240-kip load would require 42 in. of flexible pavement. The test item had 42 in. of pavement above the subgrade and indicates that the conventional item performed in accordance with the existing conventional pavement criteria.

UNCONFINED COMPRESSION TEST DATA

In addition to the test data presented in References 1-3, unconfined compression tests were conducted on several of the stabilized soils used in the test sections. The samples were laboratory prepared and tested at 28 days. The results of the unconfined compression tests are shown in Table 1.

DEVELOPMENT OF EQUIVALENCY FACTORS FOR FLEXIBLE PAVEMENT TESTS

The analysis of data used to develop equivalency factors was based upon use of the CBR design method. In the analysis procedure, it was necessary to calculate the total thickness of a conventional flexible pavement which would perform in the same manner as the test items containing stabilized layers. It was considered necessary to base these calculations on an accepted and reliable procedure and the CBR design method as developed by the Corps of Engineers and presented in TR-71-17[8] was selected.

The CBR method for determining flexible pavement thickness requirements involves the parameters of soil strength, load, traffic, thickness, and tire contact area or tire pressure. These parameters have been related through the equation

$$t = \alpha\sqrt{A}\left[-0.0481 - 1.1562\left(\log\frac{CBR}{p_e}\right) - 0.6416\left(\log\frac{CBR}{p_e}\right)^2 - 0.4730\left(\log\frac{CBR}{p_e}\right)^3\right] \qquad (1)$$

where

t = total thickness of superior material required above a layer of soil of known strength to prevent shear failure within this layer of soil, in.

α = load repetition factor which varies with the number of wheels on the main gear of the aircraft being considered and the volume of aircraft traffic or in the case of accelerated traffic tests the number of wheels on the test gear and the volume of traffic to failure of the test item

A = measured contact area of one tire, sq in.

CBR = strength of soil as determined by Test Method 101 of Military Standard MIL-STD-621A[9]

p_e = equivalent single-wheel load (ESWL) or single-wheel load (SWL) tire pressure, psi

The tire pressure, p_e, is an artificial tire pressure for multiple-wheel loads and has no relation to the actual tire inflation pressure. However, for single-wheel loads, this pressure is the average contact pressure and is nominally the same as the actual tire inflation pressure. For multiple-wheel gears, p_e = ESWL/A, and for single-wheel gears, p_e = SWL/A. The ESWL is that load on one tire of a multiple-wheel gear that will have the same effect on the pavement system as the gear itself.

The basic parameters involved in the above formula have been plotted so that the relationships shown in Figures 4 and 5 can be used rather than the above equation. Figure 4 is a plot of $t/\sqrt{A}$ versus CBR/p_e, and Figure 5 is a plot of load repetition factor α versus coverages. Total thickness t can be determined from Figure 4 if all other parameters are known and then adjusted based upon the traffic level by use of Figure 5.

In this analysis, the above criteria were used to calculate the total thickness of conventional flexible pavement required to support the traffic and load applied to the test items. This total thickness was then divided into 3 in. of asphaltic concrete (AC) and 6 in. of base, with the remainder of the thickness considered subbase. The AC and base course thicknesses were the thicknesses of base and AC used in the test sections. The AC is considered to be a high-quality AC

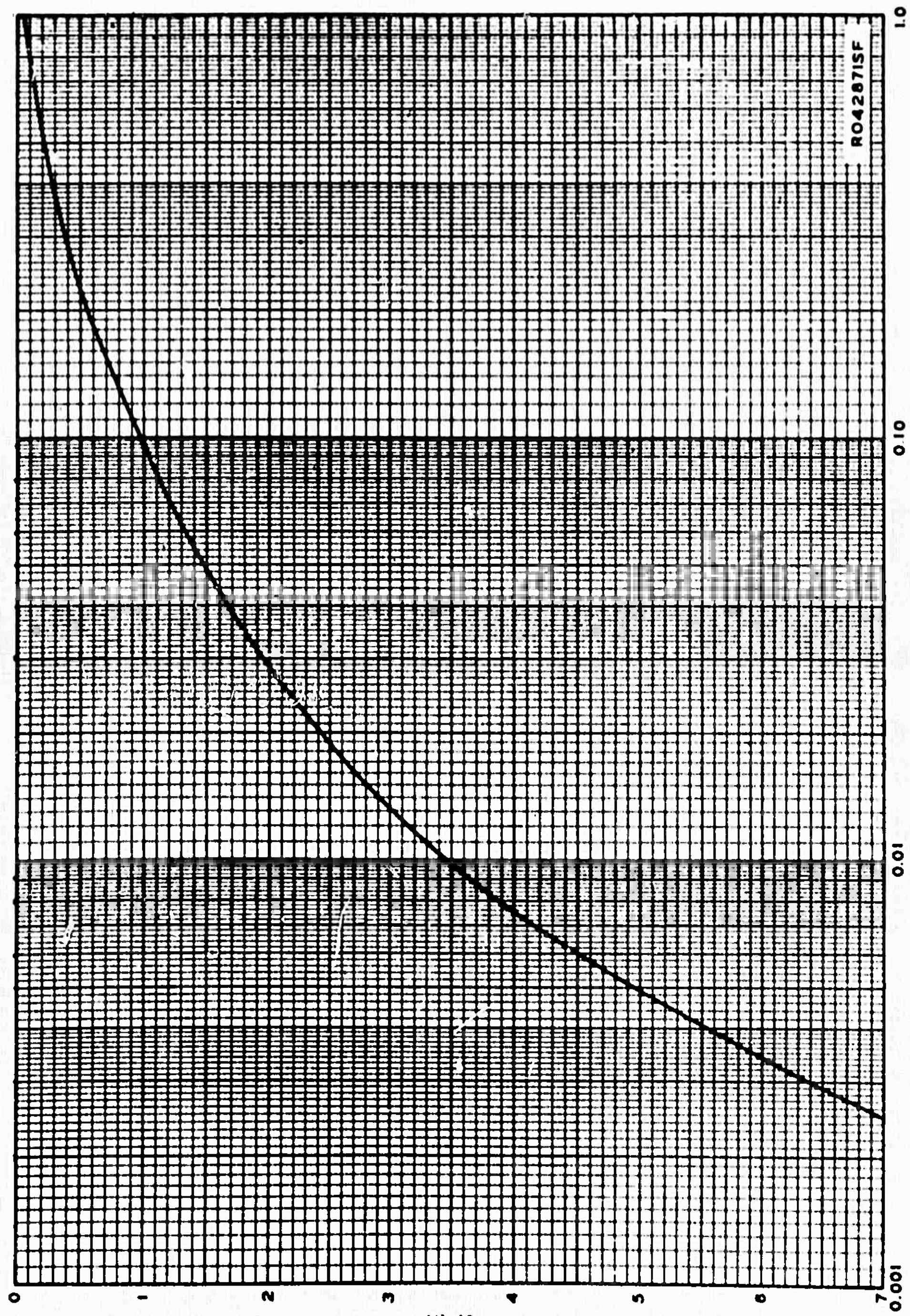


Figure 4. $\frac{t}{\sqrt{A}}$ versus $\frac{CBR}{p_e}$

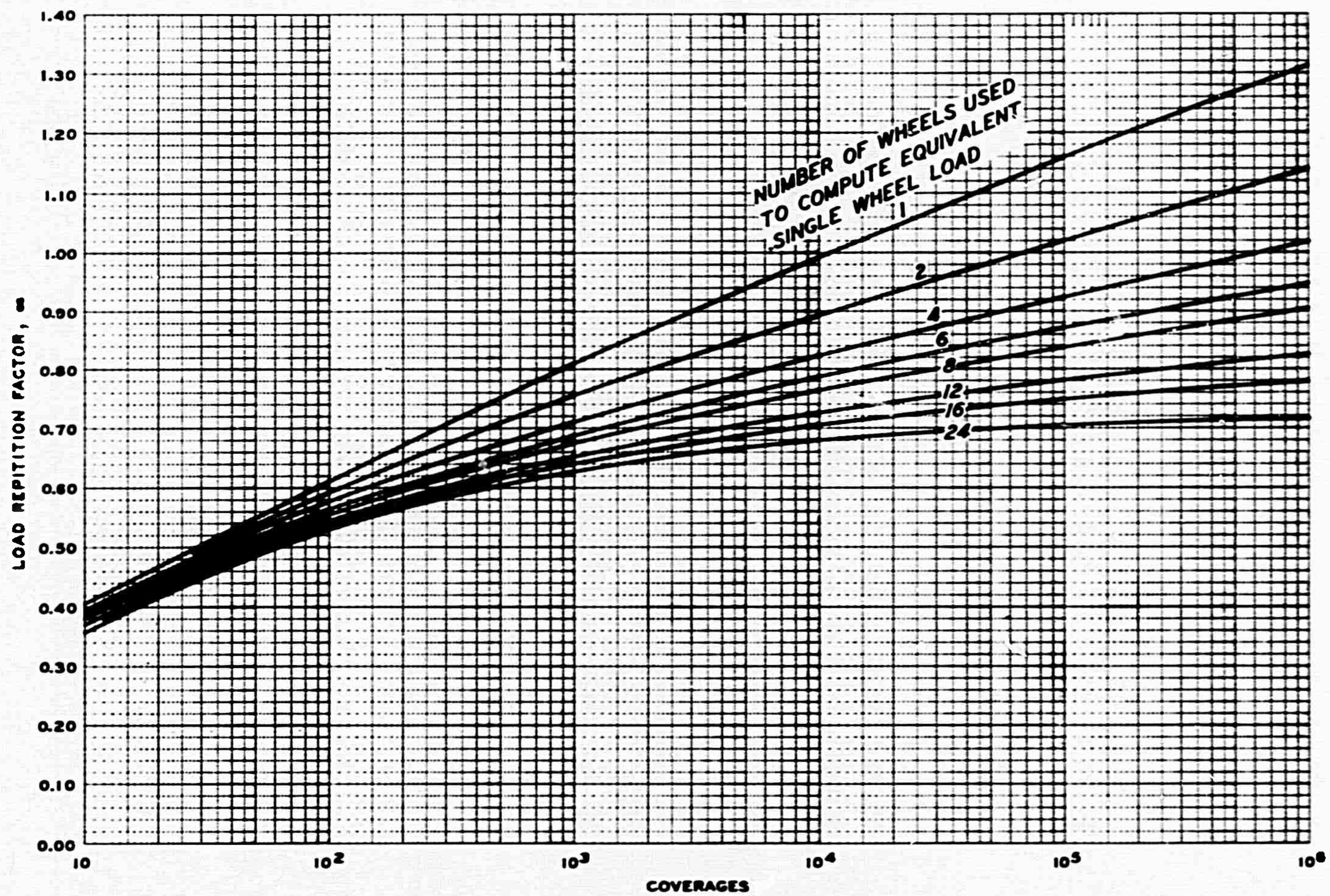


Figure 5. Load repetition factor versus coverages

meeting Federal Aviation Administration (FAA)-Office, Chief of Engineers (OCE), surface mix specifications, the base is considered to be a high-quality graded crushed aggregate meeting FAA-OCE specifications, and the subbase is considered to be a high-quality material meeting FAA-OCE specifications. The results of all calculations are shown in Table 2.

In developing equivalency factors for each of the test sections it was necessary to first find a means of relating unbound crushed stone base course material to unbound subbase material. This had to be accomplished since, in many instances, a stabilized layer in a test item replaced both the base and subbase material. To find this relationship, test identification Nos. 11 and 15 were used (Table 2). These test items consisted of 3 in. of AC and 21 in. of crushed stone on top of the subgrade. By calculating the equivalent thickness of conventional flexible pavement for identification No. 11 and designing the layer thicknesses, the AC would be 3 in., the base would be 6 in., and the subbase would be 28.5 in., which is a total of 37.5 in. as shown in Table 2.

The top 6 in. of the crushed stone layer in the test item was equal to the 6-in. conventional base, and since the thicknesses of AC were equal, then 15 in. of crushed stone in the test item replaced 28.5 in. of subbase material. Therefore, 1 in. of crushed stone was performing the same as 1.90 in. of subbase. This same calculation was done for test identification No. 15, and showed a relationship of 2.12. Considering these two values, an equivalency factor of 2.00 was selected for crushed stone in terms of subbase, which means that in all other calculations, 1 in. of crushed stone was considered equal to 2 in. of subbase. Test identification No. 19 was not considered in establishing the relationship between subbase and crushed stone, since this test item was considered to be significantly overloaded by the use of a 75-kip single-wheel load. The equivalency factor calculated reflected the magnitude of this overload in that a factor of 1.08 was calculated. This factor indicates almost a 1-to-1 relationship between a high-quality crushed stone base and a subbase

Table 2

Calculation of Equivalency Factors

Test Item Identification Number	Test Gear Arrangement	Gear Load kips	Thickness of Surface Course, in.	Base Course Thickness in.	Base Course Material	Base Course Stabilizing Agent	Subbase Course Thickness in.	Subbase Course Material	Subbase Course Stabilizing Agent	Total Test Section Thickness, in.	Subgrade CBR	Coverages to Failure	Equivalent Thickness of Conventional Flexible Pavements	Equivalency Factors
1	Twin-Tandem	200	1	6	Crushed Stone	--	24	Lean Clay	Lime, Cement, Fly Ash	33	5.6	3,660	38.6	1.2[illegible]
2	Twin-Tandem	200	1	25	Lean Clay	Cement	--	--	--	28	5.4	3,660	19.8	1.72
3	Twin-Tandem	200	3	25	Gravelly Sand	Cement	--	--	--	28	3.8	7,820	54.0	2.30
4	Twin-Tandem	200	3	25	Clayey Sand	Cement	--	--	--	28	4.9	1,390	39.0	1.68
5	Twin-Tandem	240	3	6	Crushed Stone	--	24	Lean Clay	Lime, Cement, Fly Ash	33	4.4	600	44.0	1.46
6	Twin-Tandem	240	3	25	Lean Clay	Cement	--	--	--	28	4.0	340	43.8	1.87
7	Twin-Tandem	240	1	25	Gravelly Sand	Cement	--	--	--	28	3.2	620	56.0	2.36
8	Twin-Tandem	240	3	25	Clayey Sand	Cement	--	--	--	28	5.2	120	31.0	1.36
9	12-Wheel	360	3	6	Crushed Stone	--	15	Lean Clay	Lime	24	5.0	198	25.4	1.10
10	12-Wheel	360	3	6	Crushed Stone	--	15	Lean Clay	Cement	24	4.3	1,200	34.0	1.68
11	12-Wheel	360	3	21	Crushed Stone	--	--	--	--	24	4.3	5,000	37.5	1.90
12	12-Wheel	360	3	21	Clayey, Gravelly Sand	Cement	--	--	--	24	4.2	10,406*	--	2.28
13	Twin-Tandem	160	3	6	Crushed Stone	--	15	Lean Clay	Lime	24	5.0	140	24.4	1.02
14	Twin-Tandem	160	3	6	Crushed Stone	--	15	Lean Clay	Cement	24	4.3	1,000	35.0	1.71
15	Twin-Tandem	200	3	21	Crushed Stone	--	--	--	--	24	4.3	690	41.0	2.12
16	Twin-Tandem	200	3	21	Clayey, Gravelly Sand	Cement	--	--	--	24	4.2	1,810	45.8	2.32
17	Single	50	3	6	Crushed Stone	--	15	Lean Clay	Lime	24	5.0	40	18.0	0.60
18	Single	50	3	6	Crushed Stone	--	15	Lean Clay	Cement	24	4.3	90	22.2	0.86
19	Single	75	1	21	Crushed Stone	--	--	--	--	24	4.3	38	25.2	1.08
20	Single	75	1	21	Clayey, Gravelly Sand	Cement	--	--	--	24	4.2	120	29.0	1.54
21	12-Wheel & Single	360 & 75	1	21	Clayey, Gravelly Sand	Cement	--	--	--	24	4.2	200	31.0	1.67**
22	12-Wheel	360	1	12	Gravelly Sand and Cement Filler	Bitumen	--	--	--	15	4.4	78	25.0	2.32
23	12-Wheel	360	1	6	AC	Bitumen	6	AC	Bitumen	15	4.2	425	31.7	2.90†
24	12-Wheel	360	3	6	AC	Bitumen	15	Gravelly Sand	Bitumen	24	4.9	2,198	12.2	1.68†
25	12-Wheel	360	1	6	AC	Bitumen	15	Gravelly Sand	--	24	3.8	734	35.9	4.30
26	Single	75	3	12	Gravelly Sand and Cement Filler	Bitumen	--	--	--	15	4.5	6	16.0	1.19
27	Single	75	1	6	AC	Bitumen	6	AC	Bitumen	15	4.0	8	16.0	1.78†
28	Single	75	1	6	AC	Bitumen	15	Gravelly Sand	Bitumen	24	4.9	70	25.5	1.34†
29	Single	75	3	6	AC	Bitumen	15	Gravelly Sand	--	24	4.1	12	19.7	1.30

* No failure produced at this load.
** Based upon 75-kip single-wheel load.
† Determined by combining stabilized layers.

material, which is not reasonable and was therefore not used in establishing a relationship between crushed stone and subbase material.

In calculating the equivalency factors for the stabilized layers, the following steps were followed.

a. An equivalent total thickness of conventional pavement was calculated for each test item.

b. For those test items having a thickness of AC above a single stabilized layer, the base in the conventional pavement was converted to equivalent thickness of subbase. The thickness of the stabilized layer was then compared to the thickness of subbase plus the thickness of subbase representing the base course, to determine the equivalency factor.

c. For those test items having a thickness of AC and crushed stone on a stabilized layer, it was possible to directly compare the thickness of the conventional subbase with the stabilized layer to obtain an equivalency factor.

d. Those test items containing all-bituminous concrete or having bituminous stabilized layers below the surface course were treated as a single stabilized layer in the same manner as discussed in b above. This was necessary since there was no apparent way to determine the relative effects of the separate layers.

e. For those test items having a thickness of AC over a stabilized base on an unstabilized subbase, the base in the conventional pavement was converted to an equivalent thickness of subbase material. The difference between this equivalent subbase thickness and the thickness of subbase in the test section was determined, and then compared to the thickness of stabilized base to determine the equivalency factor.

EXAMPLE EQUIVALENCY FACTOR CALCULATIONS

Example calculations showing how the equivalency factors were calculated are presented below.

a. Calculate equivalency factor for test identification No. 1 which consists of 3 in. of AC, 6 in. of crushed stone base, and 24-in. subbase of lean clay stabilized with lime, cement, and fly ash.

(1) The equivalent thickness of conventional pavement from Table 2 is 38.6 in., consisting of 3 in. of AC, 6 in. of crushed stone, and 29.6 in. of subbase. Since the test section contains AC and base, then the stabilized layer is performing only as a subbase. Therefore, the thickness

of stabilized layer can be compared directly to the thickness of subbase in the conventional pavement.

(2) The equivalency factor is therefore equal to the thickness of subbase from the conventional pavement divided by the thickness of the stabilized layer, or 29.6/24 = 1.23.

b. Calculate equivalency factor for test identification No. 2 which consists of 3 in. of AC and 25 in. of cement-stabilized lean clay.

(1) The equivalent thickness of conventional pavement is 39.8 in. from Table 2 consisting of 3 in. AC, 6 in. base, and 30.8 in. of subbase. Since the test section consists of one layer of stabilized material below the asphalt, the stabilized layer is doing the same job as the base and subbase of the conventional pavement.

(2) The 6 in. of base is converted to an equivalent thickness of 12 in. of subbase using the equivalency factor relating crushed stone to subbase.

(3) This 12 in. is then added to the subbase indicating that the stabilized layer is equivalent to 42.8 in. of subbase material.

(4) The equivalency factor is then determined by dividing 42.8 by 25, which results in a factor of 1.72. Therefore, 1.72 in. of subbase is equivalent to 1.0 in. of cement-stabilized lean clay.

SELECTION OF EQUIVALENCY FACTORS FOR DESIGN

BITUMINOUS STABILIZED LAYERS

Table 2 shows the results of equivalency factor calculations for all test items containing bituminous stabilized layers along with the values for unbound crushed stone. These data were studied and arranged in Table 3 to show the range of equivalency factors. Using these equivalency factors, representative values were determined by initially averaging the values by soil type and then rounding down to the nearest tenth of an inch. Table 4 shows the equivalency factors in terms of subbase material for bituminous stabilized soils. Also shown in this table is the equivalency relationship between unbound crushed stone and subbase material. The recommended equivalency factors were developed in terms of subbase soils and were extended

Table 3

Equivalency Factors for Bituminous Stabilized Layers and Unbound Crushed Stone

Test Item Identification Number	Description of Stabilized Layer	Equivalency Factors*
	Bituminous	
22, 26	SP, E-1, and cement filler with 2.9 percent	2.32, 1.78
23, 27	GW, E-1 - 6 in. 5 percent and 6 in. 2.9 percent	2.90, 1.76
24, 28	GW, E-1 - 6 in. 5 percent and SP with 2.9 percent	1.68, 1.34
25, 29	GW, E-1 with 5 percent	4.00, 1.30
	Unbound Crushed Stone	
11, 15, 19	GW, E-1 - base course	1.90, 2.12, 1.08

* Expressed in terms of subbase material.

Table 4

Equivalency Factors for Bituminous Stabilized Materials

Material	Equivalency Factors	
	Base	Subbase
All-bituminous concrete	1.15	2.30
GW, GP, GM, GC	1.00	2.00
SW, SP, SM, SC	----*	1.50

* Not recommended for base course.

to equivalency factors for base course soils using the 2.0 equivalency factor previously developed for crushed stone. This table therefore shows the number of inches of base or subbase material that can be replaced by 1 in. of a soil stabilized with bituminous material.

As can be seen in Table 4, the equivalency factors are shown as being applicable to soils other than those tested. It was not possible to test all soil types, so in order to make the design system usable, it was necessary to use engineering judgment coupled with experience to place other soil types into groups for which the equivalency factor could be used.

LIME, CEMENT, OR A COMBINATION
OF LIME, CEMENT, AND FLY ASH

Table 1 lists the results of the unconfined compressive strength tests and Table 2 lists the calculated equivalency factors for each test item. These data were plotted and are shown in Figure 6. Data are shown for multiple-wheel and single-wheel test results, and these data are separated with the single-wheel tests yielding low equivalency factors. These low values are considered to result from a significant overload by the single-wheel traffic, and were not included in any further analysis. After studying the multiple-wheel data in Figure 6, a limiting curve was drawn on the figure as shown by the solid line. This curve can now be used to select a design equivalency factor for stabilized soils when the unconfined compressive strength is known. The equivalency factors read from Figure 6 are for subbase material. If a particular stabilized soil is to be used for base course, the factor for subbase must be divided by 2.0 which is the equivalency factor that relates base course to subbase course material. Use of equivalency factors less than 1.0 or greater than 2.3 is not recommended. Stabilized soils used in a flexible pavement must meet the minimum strength and durability requirements set forth in TM 5-822-4[7] before an equivalency factor may be used in design.

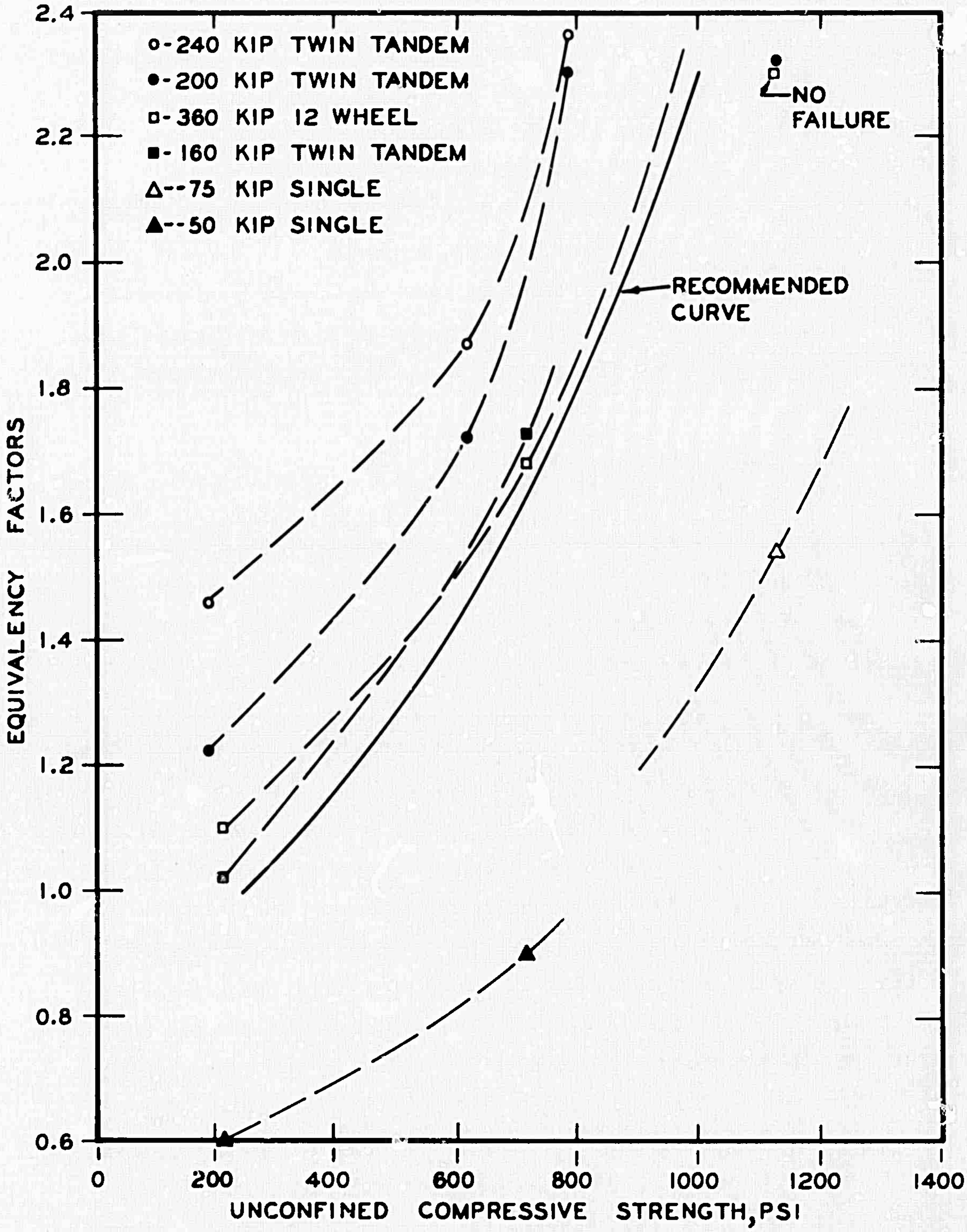


Figure 6. Equivalency factor versus unconfined compressive strength

DESIGN PROCEDURE

To design a pavement containing stabilized soil layers requires application of the equivalency factors to the layer or layers of a conventionally designed pavement. To qualify for application of equivalency factors, the structural layer must meet appropriate strength and durability requirements. The equivalency factor represents the number of inches of a conventional base or subbase which can be replaced by 1 in. of stabilized soil. To use the equivalency factors requires that a conventional flexible pavement be designed to support the design loading conditions. If it is desired to use a stabilized base or subbase course, the thickness of conventional base or subbase is divided by the equivalency factor for the applicable stabilized soil (Table 4 or Figure 6). Several examples of the application of equivalency factors are shown below:

EXAMPLE 1: USING CEMENT-STABILIZED GRAVELLY SOIL (GM) FOR BASE AND SUBBASE

Conventional Design	Equivalency Factor for Cement-Stabilized Gravelly Soil, UCS = 890	Stabilized Design
3 in. AC	--	3 in. AC
6 in. base	1.0	6 in. stabilized GM
18 in. subbase	2.0	9 in. stabilized GM

EXAMPLE 2: USING CEMENT-STABILIZED GRAVEL (GW) FOR BASE ONLY

Conventional Design	Equivalency Factor for Cement-Stabilized Gravel, UCS = 1000	Stabilized Design
3 in. AC	--	3 in. AC
8 in. base	1.15	7.0 in. stabilized GW
20 in. subbase	--	20 in. subbase

EXAMPLE 3: USING CEMENT-STABILIZED SANDY SOIL (SM) FOR SUBBASE ONLY

Conventional Design	Equivalency Factor for Cement-Stabilized Silty-Sand, UCS = 640	Stabilized Design
4 in. AC	--	4 in. AC
10 in. base	--	10 in. base
20 in. subbase	1.5	13.5 in. stabilized SM

EXAMPLE 4: USING SURFACE MIX FOR BASE AND SUBBASE

Conventional Design	Equivalency Factor for Surface Mix	Stabilized Design
4 in. AC	--	4 in. AC
8 in. base	1.15	7 in. AC
15 in. subbase	2.30	6.5 in. AC

RIGID PAVEMENT ANALYSIS

TEST SECTIONS AND DATA

Results of four test items were used to obtain data for this analysis. Three of the test items were a part of the test sections constructed under this study and reported in Reference 1. A plan and cross section of this test section are shown in Figure 7. The fourth test item was a part of the study reported in Reference 4 and a plan and cross section are shown in Figure 8. Each of the four test items was divided into two traffic lanes in which either different loads with the same gear configuration or different gear configurations were used. The performance of each traffic lane was analyzed separately making a total of eight analyses. Pertinent data required for this analysis were either extracted from References 1 and 4 or developed from field or laboratory tests especially for this analysis and are shown tabulated in Table 5.

APPROACH

The performance of each of the four test items was analyzed in the following manner in an effort to find an analysis procedure that adequately predicted the performance obtained.

a. Slabs on grade.

b. Partially bonded rigid overlay.

c. PCA adjusted radius of relative stiffness method.

The performance analyses consisted either of determining the thickness requirements which were compared to the as-constructed thickness or determining the allowable coverages (stress repetitions) which were compared to the actual coverage level causing failure.

RIGID PAVEMENT CRITERIA

Current Corps of Engineers (CE) criteria[10,11] were used to analyze the performance of the test items as slabs on grade and as partially bonded rigid overlays. The CE criteria are based upon the Westergaard edge-loading algorithm[12] assuming that load transfer

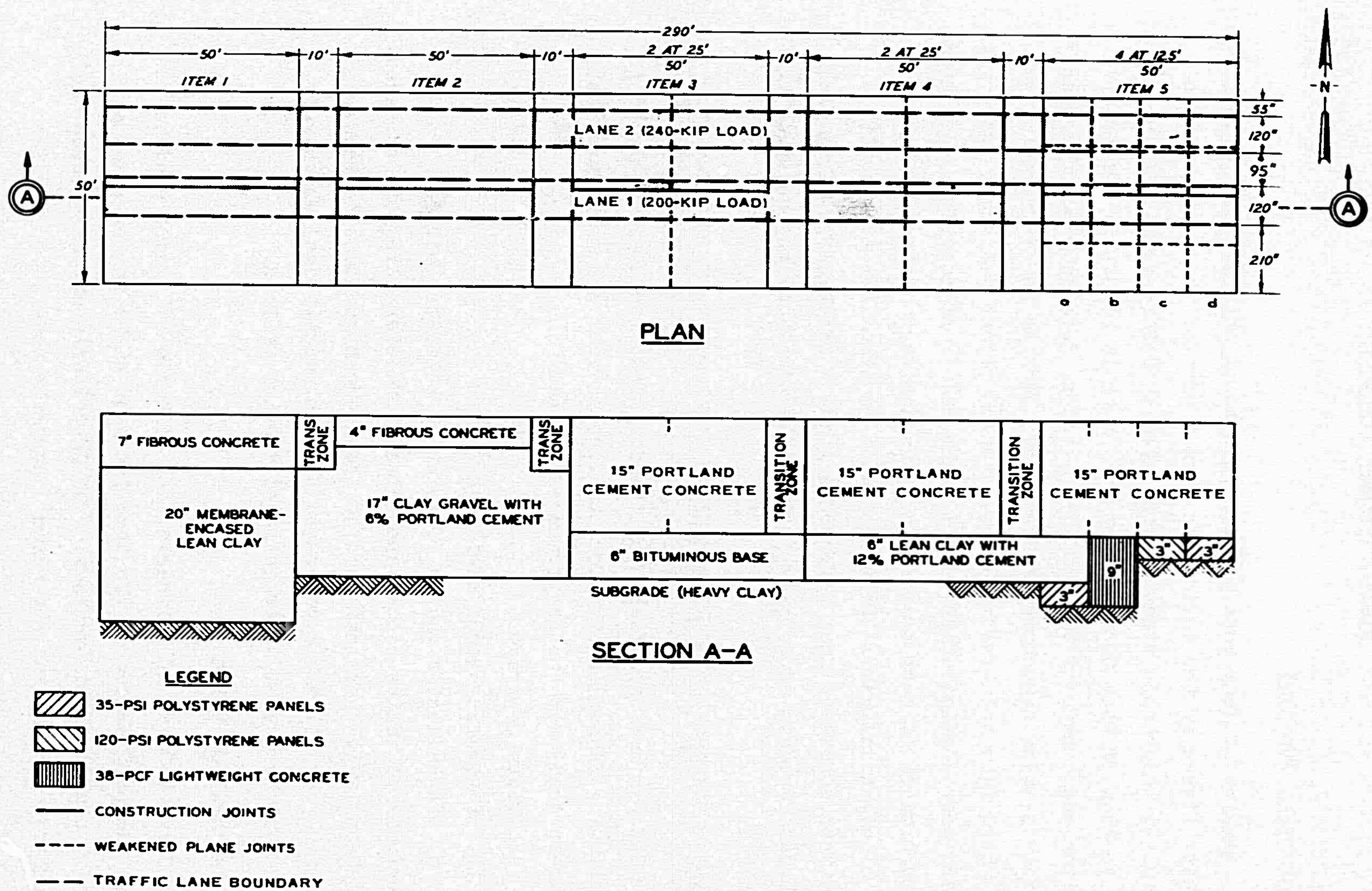


Figure 7. Layout of rigid pavement test section (after Reference 1)

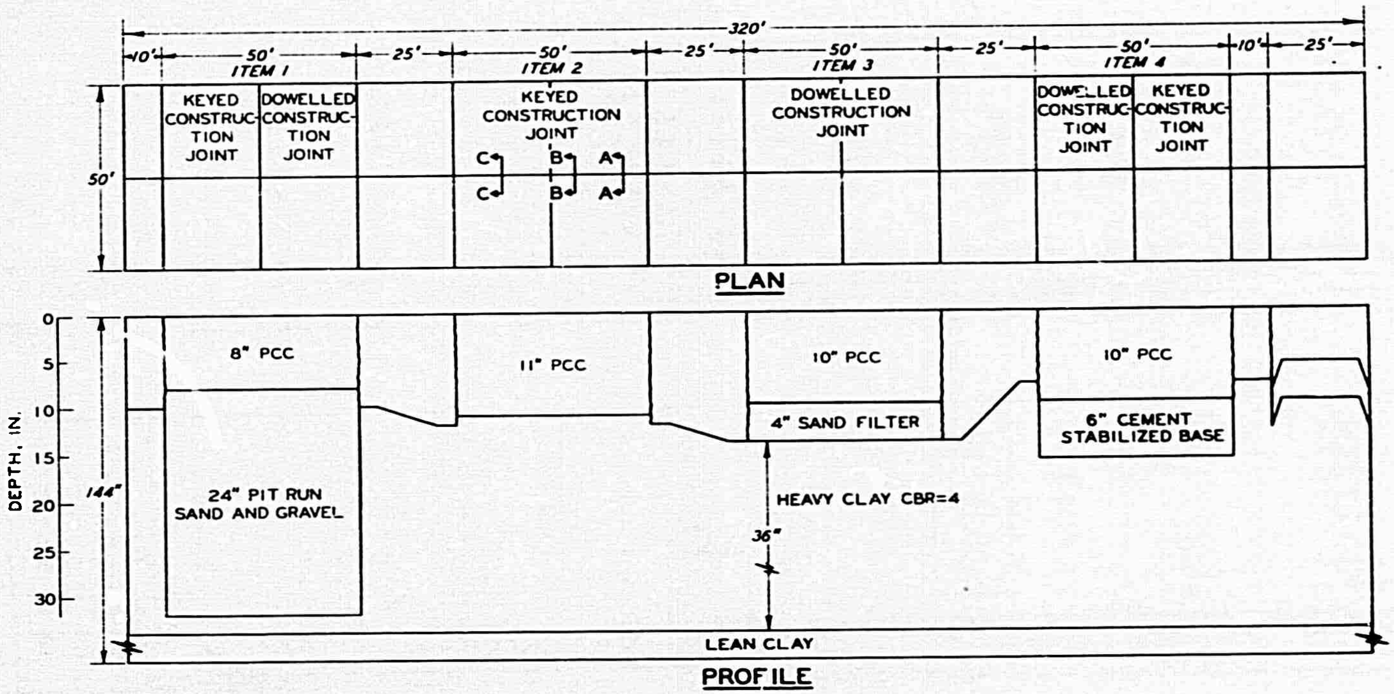


Figure 8. Layout of rigid pavement test section (after Reference 4)

Table 5

Summary of Test Section Data Used for Analysis of Performance of Rigid Pavement on Stabilized Layers

Identification				Subgrade Properties					Base Course Properties										
				Classification		k Value, psi/in.			Classification		Thickness in.	Stabilizing Agent		k Value, psi/in.				Unconfined Compressive Strength Range, psi	Flexural Strength psi
No.	Test Track	Test Item	Traffic Lane	USCS	FAA	As-Constructed	After-Traffic	Select for Analysis	USCS	FAA		Type	Percent	As-Constructed	After-Traffic	Selected as Measured	Estimated From Figure 12		
1	CPSL	2	1	CH	E-11	85	118	100	SP-SC	E-5	17	PC	6	545	490	500	260	1000-1200	115(1)
2	CPSL	2	2	CH	E-11	85	—	100	SP-SC	E-5	17	PC	6	545	375	475	260	1000-1200	115(1)
3	CPSL	3	1	CH	E-11	84	—	100	SP	E-1	6	Asphalt	4.6	99	255	255	150	—	100(1)
4	CPSL	3	2	CH	E-11	84	164	100	SP	E-1	6	Asphalt	4.6	99	—	255	150	—	90(1)
5	CPSL	4	1	CH	E-11	40	68	50	CL	E-7	6	PC	12	167	200	200	70	600-800	100
6	CPSL	4	2	CH	E-11	40	68	50	CL	E-7	6	PC	12	167	328	250	70	600-800	100
7	LJS	4	S	CH	E-11	47	—	47	SW-SC	E-5	6	PC	6	344	395	375	70	1000-1200	115(1)
8	LJS	4	N	CH	E-11	47	—	47	SW-SC	E-5	6	PC	6	344	395	375	70	1000-1200	115(1)

Table Continued

	Flexural Modulus of Elasticity $\times 10^6$, psi		Concrete Properties					Performance Data								
								Applied Gear Loading		Coverages to Failure						
										Initial Crack			Shattered Slab			
No.	Range	Select for Analysis	Thickness in.	28-Day	After-Traffic	Select for Analysis	Flexural Modulus of Elasticity $\times 10^6$ psi	Type	kips	Slab 1	Slab 2	Selected for Analysis	Slab 1	Slab 2	Selected for Analysis
1	0.18-0.37	0.25	4.4 - 5(7)	715	1177	920	4.60	Twin-Tandem	200	500	—	500	Not Applicable		
2	0.18-0.37	0.25	4.3 - 5(7)	810	1120	1000	6.41	Twin-Tandem	240	150	—	150	Not Applicable		
3	0.12-0.17(2)	0.20(3)	15	500	897	850	6.79	Twin-Tandem	200	3000	4660	3830	6360	(4)	6360
4	0.12-0.17(2)	0.13(3)	15	515	910	875	6.30	Twin-Tandem	240	350	950+	650	(4)	(4)	—
5	0.17-0.34	0.20	15	540	982	900	7.23	Twin-Tandem	200	4660	4660	4660	5500	5850	5675
6	0.17-0.34	0.20	15	470	605	600	5.87	Twin-Tandem	240	100	40	70	200	350	275
7	0.18-0.37	0.25	10	695	834(5)	860	6.50(6)	12-Wheel	360	6336	(4)	6336	(4)	(4)	(4)
8	0.18-0.37	0.25	10	765	918(5)	860	6.50(6)	Twin-Tandem	166	320	320	320	950	880+	950

Notes: (1) Estimated values based on UCS and Flexural Modulus of Elasticity.
(2) Laboratory tests performed at 75° F.
(3) Selected values based on temperatures recorded during traffic tests using Shell nomograph.
(4) Test item not trafficked to failure condition shown.
(5) Estimated as 120 percent of 28-day strength.
(6) Estimated based on data shown for 1 through 5.
(7) Thickened-edge - no load transfer device used.

devices in the jointed slabs will reduce the free edge stress by 25 percent. For multiple-wheel gears, the Westergaard algorithm becomes rather complex. A graphical solution of the equation is presented in Reference 13 and a computerized solution is presented in Reference 14. The basis for the CE criteria is presented in Reference 15. Through the use of References 13 and 14, the computation of the edge stress for the multiple-wheel gears used to traffic the four test items can be conveniently reduced to:

$$\sigma_e = \frac{6q\ell^2 N(1 - LT)}{10{,}000h^2} \tag{2}$$

where

σ_e = edge stress in psi

q = tire contact pressure, psi

ℓ = radius of relative stiffness, in.

where

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1 - \mu^2)k}}$$

E = flexural modulus of elasticity of concrete, psi

h = thickness of concrete, in.

μ = Poisson's ratio of concrete (assumed to be 0.20)

k = modulus of soil reaction, psi/in.

N = number of blocks, including fractured blocks, falling within the scaled footprint using the influence charts in Reference 13 or as computed in Reference 14. ℓ versus N charts for the gears used in this study are shown in Figure 9.

LT = load transfer (assumed to be 0.25)

The calculated edge stress is for one application of load. Extensive full-scale traffic testing of portland cement concrete slabs on grade has shown that a concrete strength equal to 1.3 times the calculated stress is required to withstand 5000 repetitions (coverages) of the applied stress. This ratio of concrete strength to computed edge

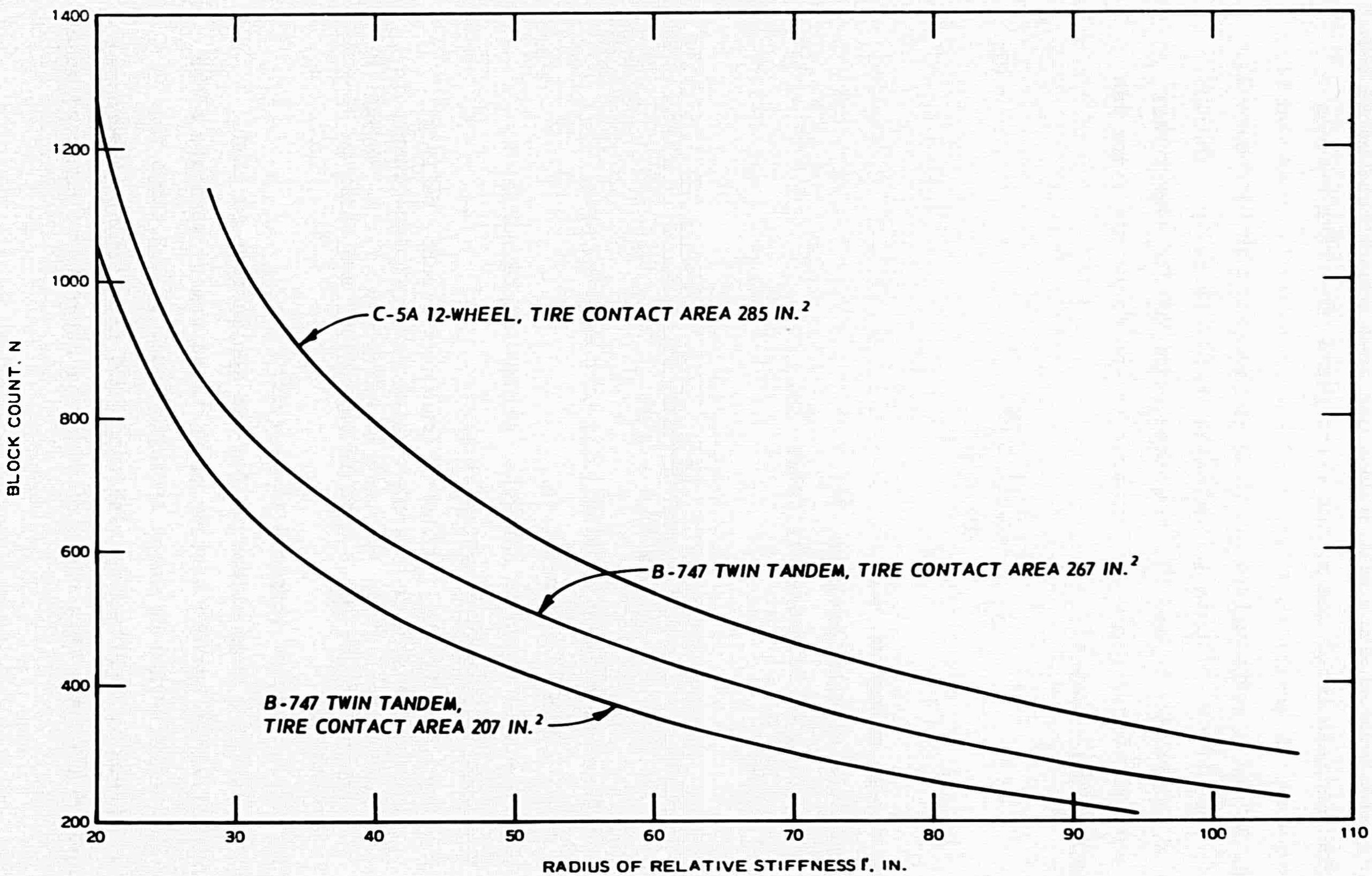


Figure 9. ℓ versus N relations

stress in the CE criteria is designated the design factor. Coverage is the manner used in the CE criteria to translate aircraft passes (traffic) into stress repetitions. Because of the transverse distribution of traffic and the complexity of wheels in aircraft landing gears, the development of pass-to-coverage ratios becomes a rather complex statistical analysis described in References 16 and 17. The thickness of pavement for which the design factor is 1.3 is designated as the standard thickness (h_s). Thus, h_s can be defined as the pavement thickness required for 5000 coverages of the applied load.

Results of full-scale accelerated traffic test sections have been used to derive relationships of the ratio (H) of h_s to the actual thickness h versus traffic coverages for various structural failure conditions. These relationships are shown in Reference 18. The failure conditions have been designated as "initial," "shattered slab," and "complete." The top line of the initial failure relationship is further designated as the "initial crack" failure condition and is shown by Figure 10 for plain concrete. This relationship was used for the analysis of the test items herein based on the development of the first crack. The relationship for the shattered slab failure condition (Figure 11) was used for the analysis of those test items which were trafficked to that condition. The H versus coverage relationship for fibrous concrete shown in Figure 10 was taken from Reference 19 and used for the analysis of the fibrous concrete test items.

Current criteria for rigid overlays to strengthen existing rigid pavements use relationships developed empirically from full-scale accelerated traffic testing. The overlay thickness requirement is based upon the deficiency between the thickness of the existing pavement (h) and the design thickness of a plain concrete pavement (h_d) if placed on the same foundation condition as that of the existing pavement. These relationships depend upon the three degrees of bond that are normally obtained between the overlay and base pavement: bonded, partially bonded, and nonbonded. The bonded condition is achieved by very deliberate treatment of the surface of the existing pavement and

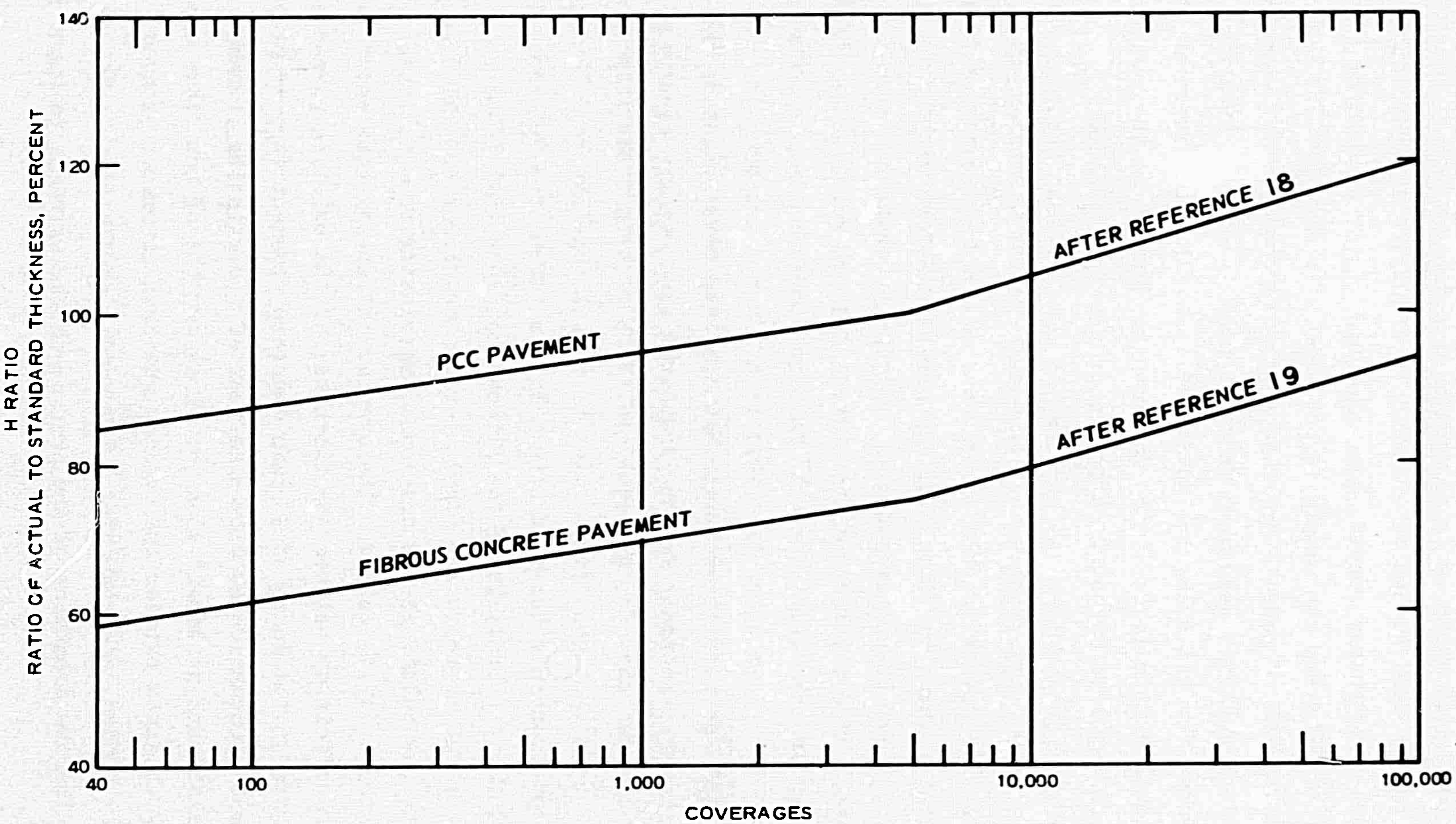


Figure 10. H-ratio versus coverages for the initial crack failure condition

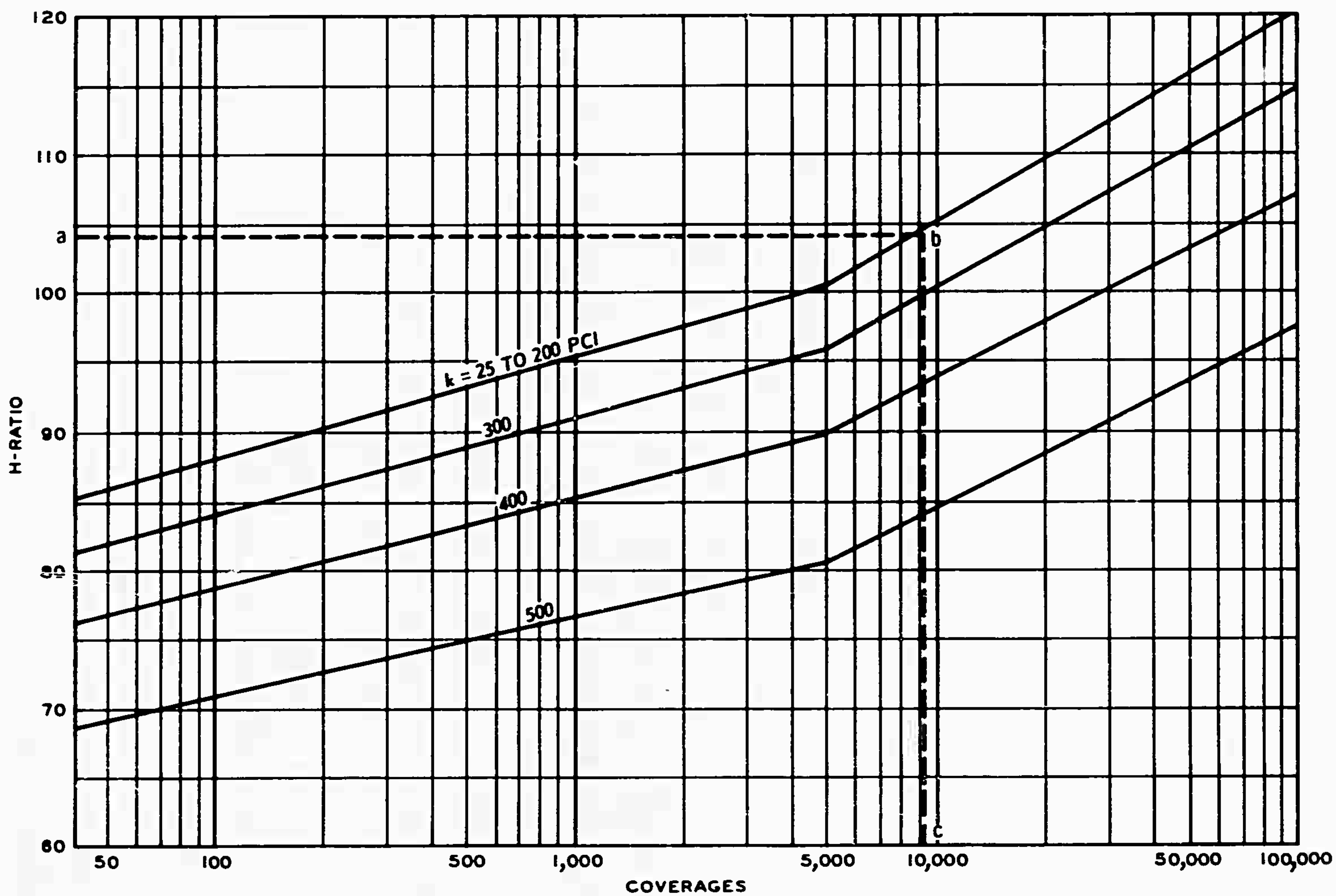


Figure 11. H-ratio versus coverages for the shattered slab failure condition

application of a bonding agent. The partially bonded is the normal condition and is achieved when the overlay is cast on the existing pavement with no special cleaning or bonding treatment. The nonbonded condition is achieved whenever a deliberate bond-breaking medium is placed on the surface of the existing pavement prior to placement of the overlay pavement. The four test items considered herein were analyzed as partially bonded overlays using the following relationship:[15]

$$h_o^{1.4} = h_d^{1.4} - C\left(\frac{h_d}{h_{db}} \times h_b\right)^{1.4} \tag{3}$$

where

h_o = required overlay thickness, in.

h_d = design thickness, in., of plain concrete having same modulus of elasticity and flexural strength as overlay pavement if placed on the same foundation as the existing pavement

C = condition factor based upon the structural condition of the existing pavement at the time of overlay (1.0 used for the analysis contained herein since both stabilized layer and overlay were new)

h_{db} = design thickness, in., of plain concrete having same modulus of elasticity and flexural strength as the existing pavement if placed on the same foundation as the existing pavement

h_b = thickness of existing (base) pavement, in.

Ordinarily the expression h_d/h_{db} in the above equation is not required because the moduli of elasticity and flexural strengths of the overlay and existing pavements are about equal and this expression approximates 1.0. However, for this analysis, the stabilized soil layer is considered to be the existing pavement and since it has moduli and strength values significantly different than the overlaying rigid pavement the h_d/h_{db} expression will become important.

If it is assumed that the modulus of elasticity of the layers is proportional to the flexural strength and therefore proportional to the thickness of the layers, then the following equation may also be used to analyze the soil stabilization data:

$$h_o^{1.4} = h_d^{1.4} - C\left(\sqrt[3]{E_{sb}/E_{co}} \times h_b\right)^{1.4} \quad (4)$$

where

E_{sb} = modulus of elasticity of the stabilized base

E_{co} = modulus of elasticity of the concrete overlay

ANALYSIS AS SLAB ON GRADE

The CE criteria were used to determine the thickness of rigid pavement that would be required to sustain the coverage level for the initial crack and, when applicable, the shattered slab failure conditions were reached. Two analyses were made; the first using the k value measured on the surface of the stabilized layer and the second by estimating the k value of the stabilized layer using the relationship shown by Figure 12. The latter analysis assumes that the stabilized layer performs similarly to a high-quality unbound base course.

Pertinent data pertaining to the physical properties of the materials and performance of the four test items (8 data points) are summarized in Table 5. The first step in the analysis is to determine the standard thickness, h_s , or the thickness of concrete having the same properties as the test slab that would be required to support 5000 coverages of the applied loading. This is a trial-and-error process in which the computed edge stress (σ_e) using Equation 2 is plotted versus thickness, h , and the h_s value picked off at a stress equal to the measured concrete flexural strength divided by the design factor (1.3). The values of h_s thus determined for the analysis using the measured k value on the stabilized layer are shown by column 5 of Table 6. The ratio H (column 8) of h_s to design thickness (h_d) of pavement required for the failure coverage levels shown in columns 10 and 11 are determined from the appropriate Figures 10 or 11. Finally, h_d is determined by multiplying h_s by H . h_d is then the thickness of concrete pavement having the same properties (E , R , μ , and k) as the test item that would be required by the criteria to sustain the coverages of the applied load indicated for each of the failure conditions. A plot of h (the existing thickness) versus h_d (the design thickness) is shown by Figure 13a.

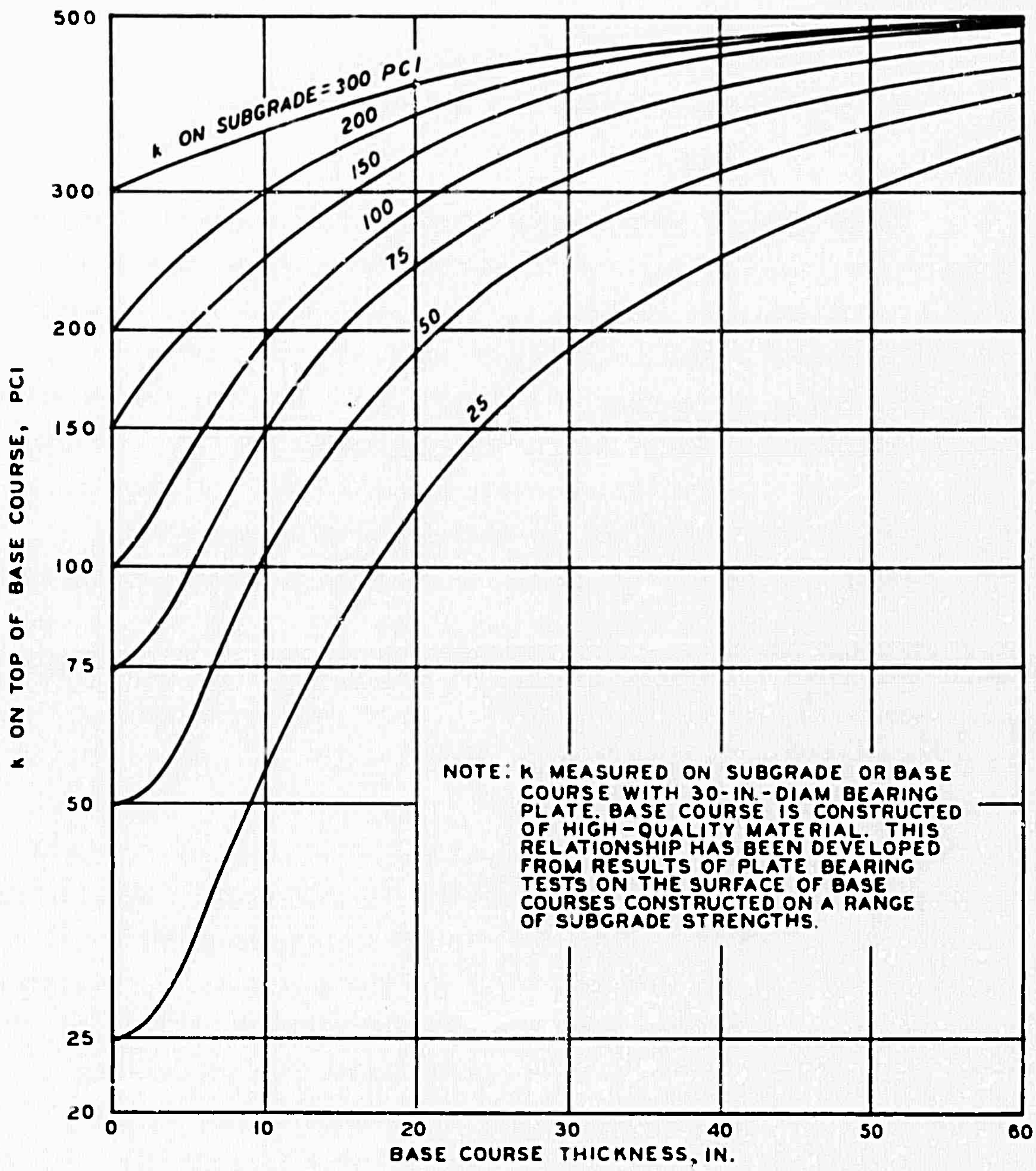


Figure 12. Soil strength k versus base course thickness

Table 6

Analysis of Performance Based on Measured Base Course k

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Pavement Thickness	Modulus of Soil Reaction, k , psi/in.		h_s	Initial Crack Failure		Shattered Slab Failure		Failure Coverage Level	
Identification	h , in.	Subgrade	Base	in.	H	h_d	H	h_d	Initial Crack	Shattered Slab
1	4.4 - 5*	100	500	8.6	67.0	5.8	--	--	500	--
2	4.3 - 5*	100	475	10.5	63.0	6.6	--	--	150	--
3	15	100	255	12.2	99.1	12.1	91	11.1	3830	6360
4	15	100	255	13.7	93.5	12.8	--	--	650	--
5	15	50	200	12.6	99.8	12.6	92.5	11.7	4660	5675
6	15	50	250	19.2	86.8	16.7	68	13.0	70	275
7	10	47	375	8.4	101.5	8.5	--	--	6336	--
8	10	47	375	9.7	91.4	8.9	68	6.6	320	950

* Thickened-edge - no load transfer device.

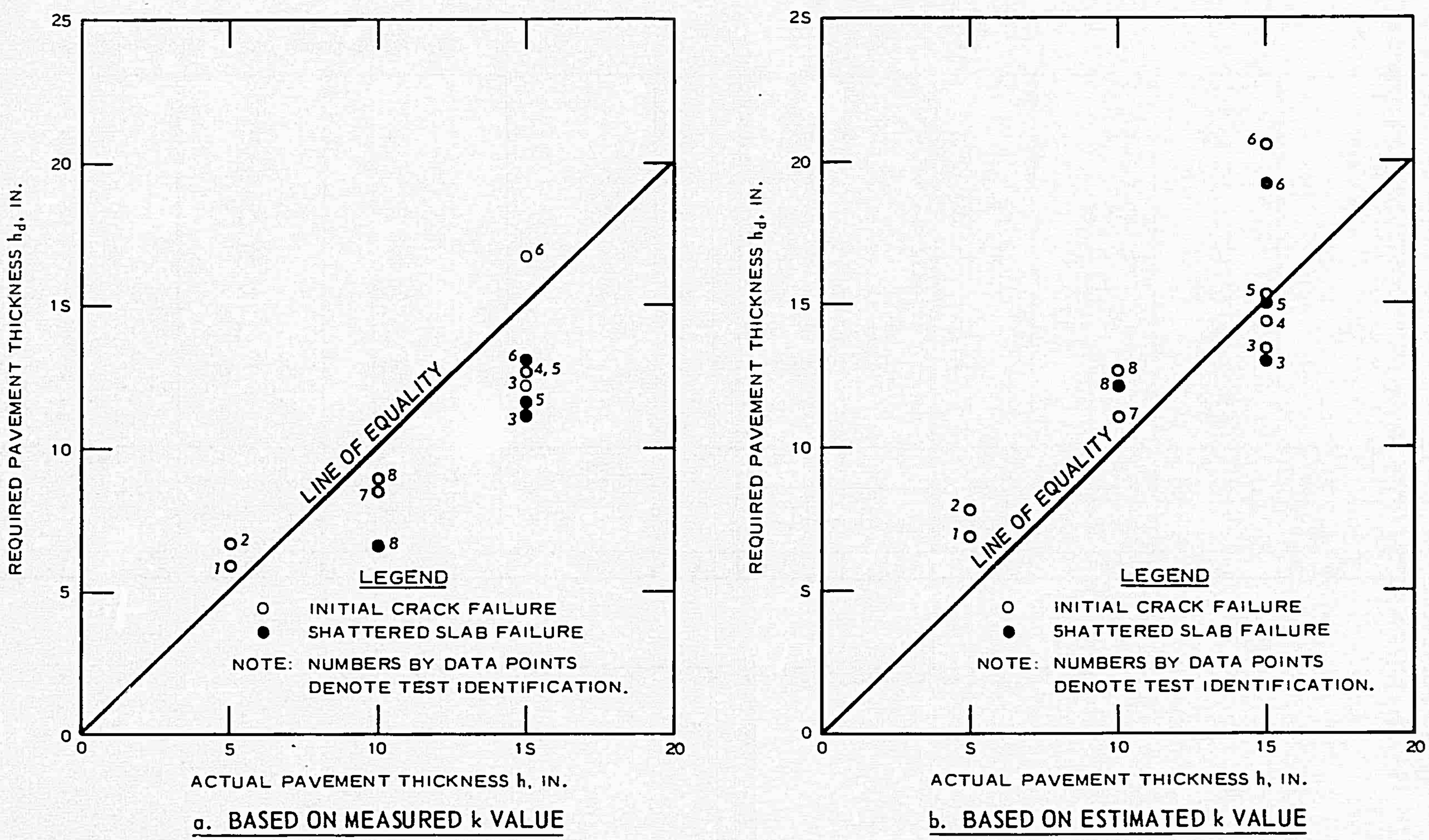


Figure 13. Analysis of performance using slab on grade analysis

Analysis of the test items using the estimated k value on the surface of the stabilized layer is performed in the same manner and the results are shown in Table 7 and plotted in Figure 13b. The k value is estimated by entering Figure 12 with the thickness of the stabilized layer and the measured k value of the subgrade.

ANALYSIS AS PARTIALLY BONDED RIGID OVERLAY

In this analysis, the stabilized layer was considered to be an existing base pavement, h_b, and the pavement was considered to be a rigid overlay, h_o. The CE criteria (Equation 3) were used to determine the thickness of rigid overlay (h_{do}), having the same properties as the pavement, that would be required over the base pavement (stabilized layer) to yield the performance (coverages to failure) as the existing test section. The procedure is essentially the same as that described for slabs on grade and the results of the analyses are summarized in Table 8. It is necessary to determine the standard thickness (h_{so}) of concrete having the same properties (E, μ, R, and k) as the existing concrete slab and the standard thickness (h_{sb}) of concrete having the same properties (E, μ, R, and k) as the base pavement (stabilized layer). These are determined by trial and error using Equation 2 and are shown by columns 6 and 7 of Table 8. H (columns 8 and 12 of Table 8) is then determined by entering Figures 10 and 11 with the coverage levels that produced the initial crack and shattered slab failure conditions, respectively. The design thicknesses (h_{do} and h_{db}) of concrete having the properties of the existing pavement and stabilized layers, respectively, are determined by multiplying the h_{so} or h_{sb} by the respective H. These values are shown by columns 9, 10, 13, and 14 in Table 8. The required thickness of overlay, h_o, is then computed using Equation 3 and is shown in columns 11 and 16 of Table 8. This h_o is the thickness of overlay required by the CE criteria over the stabilized layer to produce the same performance as the test items. A plot of the computed h_o versus the thickness of the concrete for each test item is shown by Figure 14.

Table 7

Analysis of Performance Based on Estimated k Value of Base Assuming Stabilized Layer to be Equivalent to Unbound High-Quality Crushed Stone

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Pavement Thickness	Base Thickness	Modulus of Soil Reaction, k, psi/in.			Initial Crack Failure		Shattered Slab Failure		Failure Coverage Level	
Identification	h, in.	in.	Subgrade	Estimated Base	h_s in.	H	h_d	H	h_d	Initial Crack	Shattered Slab
1	4.4 - 5*	17	100	260	10.3	67.0	6.9	--	--	500	--
2	4.3 - 5*	17	100	260	12.4	63.0	7.8	--	--	150	--
3	15	6	100	150	13.4	99.1	13.3	96.0	12.9	3830	6360
4	15	6	100	150	15.4	93.5	14.4	--	--	650	--
5	15	6	50	70	15.3	99.8	15.3	98.0	15.0	4660	5675
6	15	6	50	70	23.7	86.8	20.6	81.0	19.2	70	275
7	10	6	47	70	10.8	101.5	11.0	--	--	6336	--
8	10	6	47	70	13.8	91.4	12.6	88.0	12.1	320	950

* Thickened-edge - no load transfer device.

Table 8

Analysis of Stabilized Layer Performance Using Rigid Overlay Criteria

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
	Actual Thickness		Coverages to Failure				Initial Crack Failure					Shattered Slab Failure				
Identification	Pavement h_o, in.	Base h_b, in.	Initial Crack	Shattered Slab	h_{so} in.	h_{sb} in.	H	h_{do} in.	h_{db} in.	h_o** in.	h_o† in.	H	h_{do} in.	h_{db} in.	h_o** in.	h_o† in.
1	4.4 - 5*	17	500	--	13.0	38.0	67.0	8.7	35.3	7.6	6.61	--	--	--	--	--
2	4.3 - 5*	17	150	--	15.0	44.3	63.0	9.4	39.5	7.2	5.7	--	--	--	--	--
3	15	6	3830	6360	14.8	41.0	99.1	14.2	40.6	13.5	13.6	96.5	14.3	39.6	13.6	13.7
4	15	6	650+	--	16.6	47.5	93.5	15.5	43.6	15.9	15.0	--	--	--	--	--
5	15	6	4660	5675	16.0	44.5	99.8	16.0	44.4	15.3	15.3	99.0	15.8	40.1	15.0	15.25
6	15	6	70	275	23.7	48.4	86.8	20.6	42.0	19.7	20.2	83.0	19.7	40.2	18.6	19.14
7	10	6	6336	--	12.5	28.0	101.5	12.7	28.4	9.8	12.0	--	--	--	--	--
8	10	6	320	950	14.7	38.8	91.4	13.4	35.5	12.6	12.7	90.0	13.2	34.9	12.4	12.53

Note: Pavement for each test item assumed to be a concrete overlay, h_o . The stabilized layer base course assumed to be a base pavement, h_b . A partial bond is assumed between overlay and base pavements.

* Thickened-edge thickness - no load transfer device.
** Using current CE criteria (Equation 3).
† Using alternate analysis method (Equation 4).

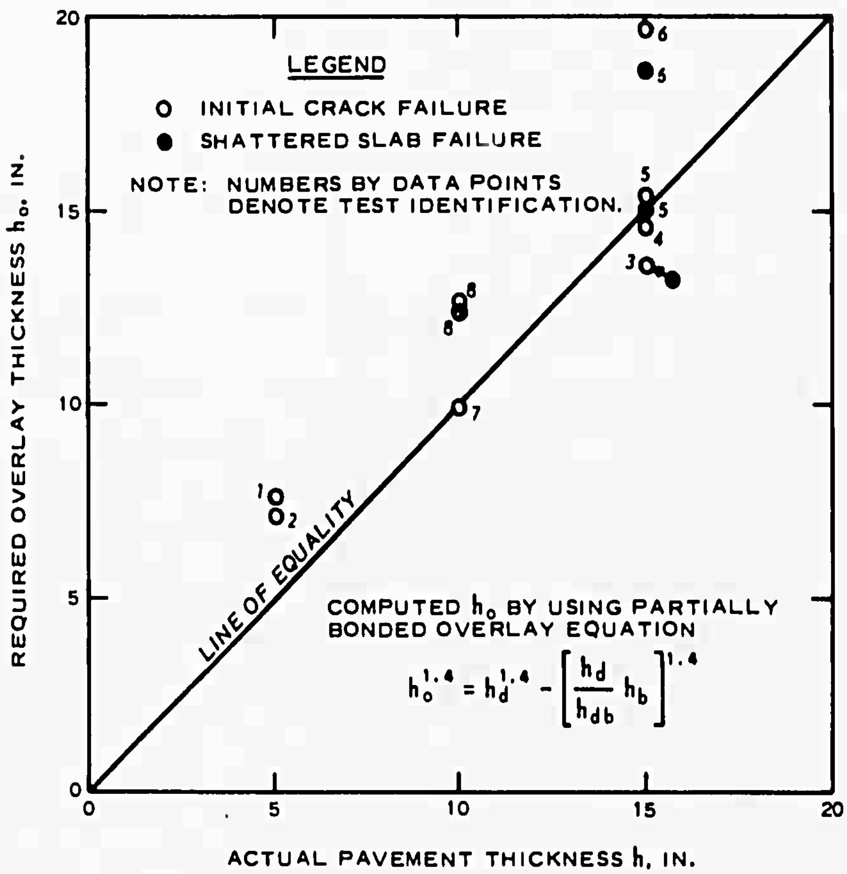


Figure 14. Analysis of stabilized layer performance using rigid overlay equation

The alternate equation (Equation 4) requires application of the same procedures and considerations as applied for the CE criteria, except the modulus of elasticity ratios are used rather than thickness ratios. These modulus values are shown in Table 5. The thickness of overlay, h_o, required by the alternate equation, is shown in columns 12 and 17 of Table 8. A plot of the computed h_o versus the thickness of the concrete for each test item is shown by Figure 15.

ANALYSIS USING PORTLAND CEMENT ASSOCIATION CONCEPT OF ADJUSTED ℓ VALUES

Appendix B of Reference 20 contains a method for the analysis of concrete pavements constructed on stabilized layers. The methodology contained therein was used to analyze the four test items and a summary of the results of that analysis is shown in Table 9. The concept of the PCA methodology is that a strong base, such as a stabilized layer, should increase the load-spreading capability of the pavement--that is, in effect increase the radius of relative stiffness, ℓ. By means of a three-layer elastic analysis, the relationship of ratio of modulus of concrete to modulus of stabilized layer versus relative change in pavement stiffness was developed and shown as Figure B1 of Appendix B to Reference 20. This relationship was used to determine the increase in the radius of relative stiffness, ℓ, for the pavements in the four test items (columns 2 through 12 of Table 9). Figure B2 of Reference 20 was developed to permit determination of the flexural stress for interior loading (σ_i) resulting from the increased radius of relative stiffness; however, the limits of the chart did not permit analysis of the range of thicknesses and performance incumbent in the four test items. Therefore, σ_i was computed (column 13) for the thickness of pavement represented by the increased ℓ' value as follows:

$$h' = \sqrt[3]{\frac{(\ell')^4 \, 12(1 - \mu^2)k}{E}}$$

and

$$\sigma_i = \frac{6qF}{(h')^2}$$

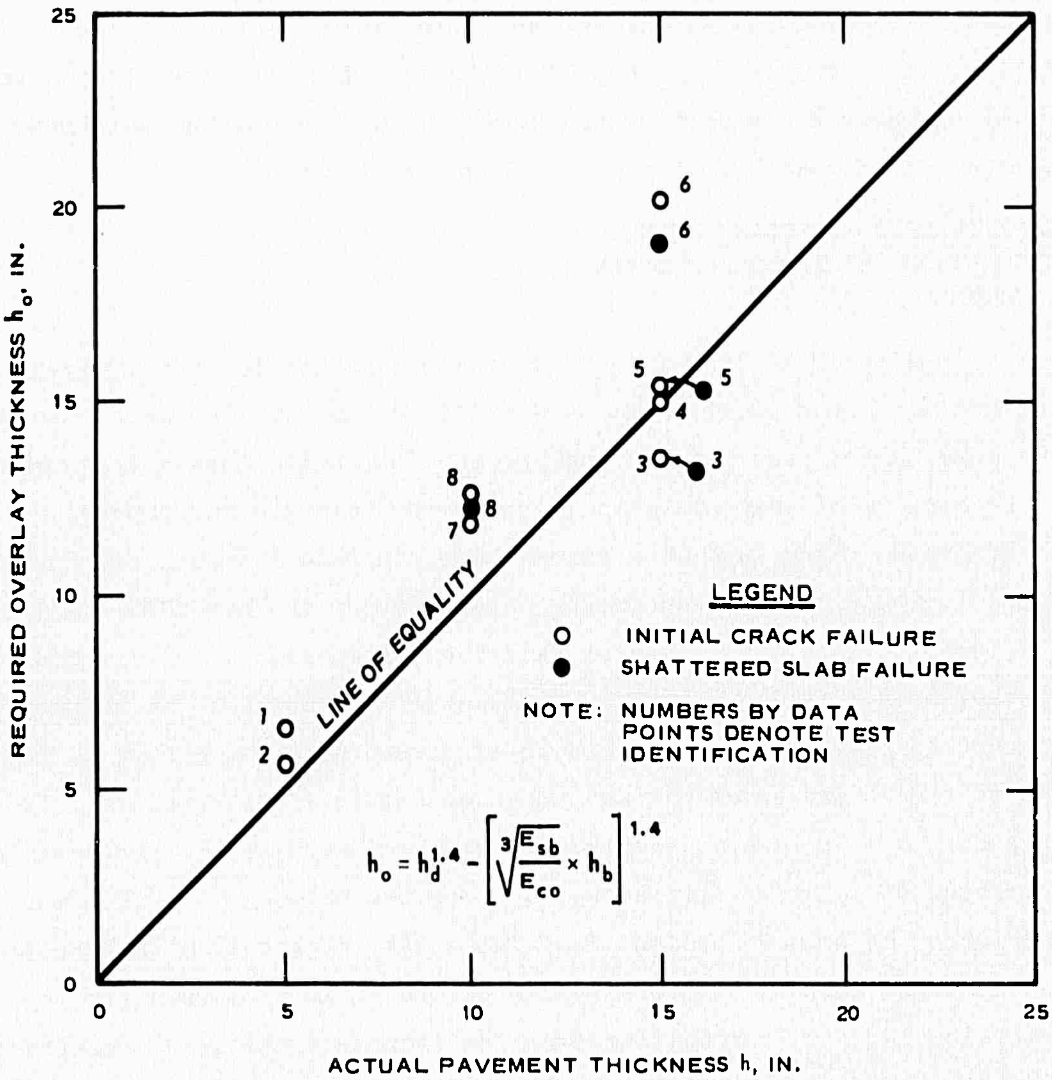


Figure 15. Analysis of stabilized layers using modified rigid overlay equation

Table 9

Analysis of Stabilized Layer Performance Using PCA Adjusted ℓ Value Concept and Interior Load Analysis

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
	Thickness, in.		Ratio	Modulus of Elasticity $\times 10^6$ psi		Ratio				Subgrade		Flexural Stress	Flexural Strength	Stress Ratio	Allowable Stress	Actual
Identification	Base	Pavement	h_p/h_b	Base, E_b	Pavement, E_c	E_c/E_b	ℓ	r	ℓ'	k, psi/in.	h_ℓ'	σ_i, psi	R, psi	σ_i/R	Repetitions	Coverages
1	17	5*	0.29	0.25	4.6	18.4	26.6	1.240	33.0	100	6.6	1339	920	1.46	<100	500
2	17	5*	0.29	0.25	6.4	25.6	28.9	1.215	35.1	100	6.5	1773	1000	1.77	<100	150
3	6	15	2.5	0.20	6.8	34.0	66.8	1.048	70.0	100	15.9	468	850	0.55	110,000	3830
4	6	15	2.5	0.13	6.3	48.5	65.5	1.042	68.2	100	15.8	558	875	0.64	9,000	650
5	6	15	2.5	0.20	7.2	36.0	80.6	1.047	84.4	50	15.9	541	900	0.60	40,000	4660
6	6	15	2.5	0.20	5.9	29.5	76.7	1.050	80.5	50	16.0	622	600	1.04	<100	70
7	6	10	1.7	0.25	6.5	26.0	58.9	1.080	63.6	47	11.0	512	860	0.59	50,000	6336
8	6	10	1.7	0.25	6.5	26.0	58.9	1.080	63.6	47	11.0	967	860	1.12	<100	320

* Thickened-edge thickness - no load transfer.

where

h' = thickness computed using increased radius of relative stiffness (ℓ'), in.

k = modulus of soil reaction, psi/in.

E = flexural modulus of elasticity of concrete, psi

q = tire contact pressure, psi

$F = \frac{N\ell'^2}{10,000}$ where N is the number of blocks under the contact area from interior load influence chart[13] or is the bending moment/contact pressure from the computer described in Appendix C[20]

The stress ratio (σ_i/R) was then computed (column 15) and used to enter Figure A3 of Reference 20 to determine the allowable number of stress repetitions (column 16).

SUMMARY OF ANALYSES

The results of the analyses can be readily visualized by examination of Figures 13 and 14 and by comparing columns 16 and 17 of Table 9. In Figures 13 and 14, data falling to the right or left of the line of equality indicate that the analysis method used underpredicted or overpredicted the required thickness, respectively, based upon the actual performance. That is, a data point falling to the right of the line of equality indicates that that analysis method gave the stabilized layer more structural credit than the performance data indicated that it provided. Thus, if that analysis method were used for design, it would result in unconservative thickness requirements. Based upon this criterion, the analysis using the partial bonded overlay equation (Figure 14) appears to provide the best fit of the data. It is pointed out that test item 6 had an exceptionally low flexural strength as compared to the other test items constructed using the same concrete which may explain why these data points seem to fall farthest from the average of the other data.

An examination of columns 16 and 17 of Table 9 shows that the PCA adjusted ℓ method grossly overpredicts the performance of four tests while it underpredicts the performance of three tests and gives a

reasonable prediction on one test. It appears that the procedure underpredicts those items that are rather severely overloaded (i.e., flexural stress equals or exceeds the concrete flexural strength) while it overpredicts those items where the flexural stress is significantly less than the concrete flexural strength. This would indicate that the slope of the stress ratio versus stress repetition relation (Figure A3 of Reference 20) should be steeper. It is also interesting to note that the stress ratio of four items exceeded 1.0 and yet these items carried from 70 to 500 coverages of traffic before the first crack was visible.

DEVELOPMENT OF DESIGN PROCEDURE

The analyses of the performance of the four rigid pavement test items incorporating stabilized soil base courses indicate that the partially bonded rigid overlay and the slab on grade using the estimated k value provide the best correlation of predicted to actual thicknesses of rigid pavement. The partially bonded rigid overlay method provides a more rational approach to the analysis since it considers the measured properties of both the concrete and stabilized soil materials and, thus, Equation 3 has been selected for the design of rigid pavements on stabilized soil layers. Equation 3 was selected over the alternate Equation 4 until such time as it can be shown that the ratio of the modulus values is proportional to the thickness ratios.

The step-by-step procedure for the design of rigid pavements using Equation 3 is as follows:

- a. Establish the modulus of soil reaction for the subgrade in accordance with Reference 9.
- b. Establish the design flexural strength and flexural modulus of elasticity for the portland cement concrete in accordance with References 21 and 22.
- c. Establish the mix proportioning and density requirements for the stabilized soil layer in accordance with Reference 7.
- d. Determine the design flexural strength and flexural modulus of elasticity of the portland cement, lime, fly ash, or combinations thereof of stabilized soil in accordance with test procedures contained in References 21 and 22.

e. Determine the design flexural strength and flexural modulus of elasticity of a bituminous stabilized soil in accordance with References 21 and 22 as modified by Appendix B of this report.

f. Determine the design thickness, h_d , for both the portland cement concrete and stabilized soil that would be required, if placed directly on the subgrade, to carry the design loading and volume of traffic in the following manner:

(1) First determine the standard thickness, h_s , of pavement having the properties of the concrete and stabilized soil if placed on the subgrade k . This is a trial-and-error process involving Equation 2. That is, the h_s will be the thickness that will have a computed edge stress equal to the design concrete flexural strength divided by the design factor (1.3). The most convenient way for solving for h_s is to select a range of thickness which will bracket h_s and compute the edge stress for each. The stresses are then plotted versus the thickness and the value of h_s determined from the plot at a stress level of $R/1.3$. Equation 2 can be solved manually using the influence charts in Reference 13 or the equation can be solved using the computer program in Reference 14.

(2) The next step is to determine the appropriate value of H (ratio of h_s/h) by entering Figure 10 with the design coverage level. The design coverage level is obtained by dividing the design pass level by the pass-per-coverage ratio (P/C) for the design aircraft. The P/C ratio can be selected from Reference 16.

(3) The design thickness, h_d , for the rigid pavement or stabilized layer that would be required to support the design loading is obtained by multiplying the h_s value by the H value. It will be noted that two values of h_d will be required; the h_{do} which is the thickness of rigid pavement that for this procedure is considered to be an overlay pavement and h_{db} which is the thickness of stabilized layer that for this procedure is considered to be the base pavement.

g. The final step on the design is then to determine the required thickness of rigid (overlay) pavement for a preselected thickness of stabilized layer (base) pavement using Equation 3. It is advantageous to select two or three thicknesses of stabilized layer and determine the resulting thicknesses of rigid (overlay) pavement and through an economic study, decide the best combination of thicknesses.

EXAMPLE DESIGN

The following example is used to illustrate the above-described design procedure. It is desired to design a rigid pavement runway end with a cement-stabilized soil layer as a base to support 100,000 passes of a B-747 aircraft at a design gross loading of 700,000 lb. The tire contact area is 207 sq in. and the tire contact pressure is 200 psi. Through a field and laboratory test program it has been determined that the subgrade material classified as a clayey sand (SC-A3), the modulus of soil reaction, k, is 200 psi/in., the percent cement to be used to stabilize the SC material will be 6 percent, the design flexural strength of the cement-stabilized soil (R) will be 125 psi, the flexural modulus of the cement-stabilized soil (E) will be 0.3×10^6 psi, the design flexural strength of the concrete (R) will be 750 psi, and the flexural modulus of elasticity of the concrete (E) will be 5.3×10^6 psi.

a. The first step is to determine the design thickness, h_d, for the concrete and stabilized soil, if placed on the subgrade, to support the design loading. To do this, it is necessary to establish the standard thickness, h_s, of each material if placed on the subgrade. This is a trial-and-error process using Equation 2 to determine thickness which will yield an edge stress of 750/1.3 = 577 psi for the concrete and 125/1.3 = 96 psi for the cement-stabilized soil. By selecting thicknesses of 12, 14, and 16 in. of concrete and thicknesses of 20, 30, and 40 in. of cement-stabilized soil, the computed edge stresses would be:

Concrete		Stabilized Soil	
$\ell_{12} = 44.7$	$\sigma_e = 544$	$\ell_{20} = 31.9$	$\sigma_{e_{20}} = 144$
$\ell_{14} = 50.1$	$\sigma_e = 485$	$\ell_{30} = 43.3$	$\sigma_{e_{30}} = 90$
$\ell_{16} = 55.4$	$\sigma_{e_{16}} = 410$	$\ell_{40} = 53.7$	$\sigma_{e_{40}} = 64$

The σ_e values are then plotted as shown in Figure 16 and the h_s values picked off at σ_e values of 577 psi and 96 psi for the concrete and stabilized soil, respectively, which are 12.15 (12.2) and 28.5 in. From Reference 16 it is found that the pass-per-coverage, P/C, ratio for the B-747

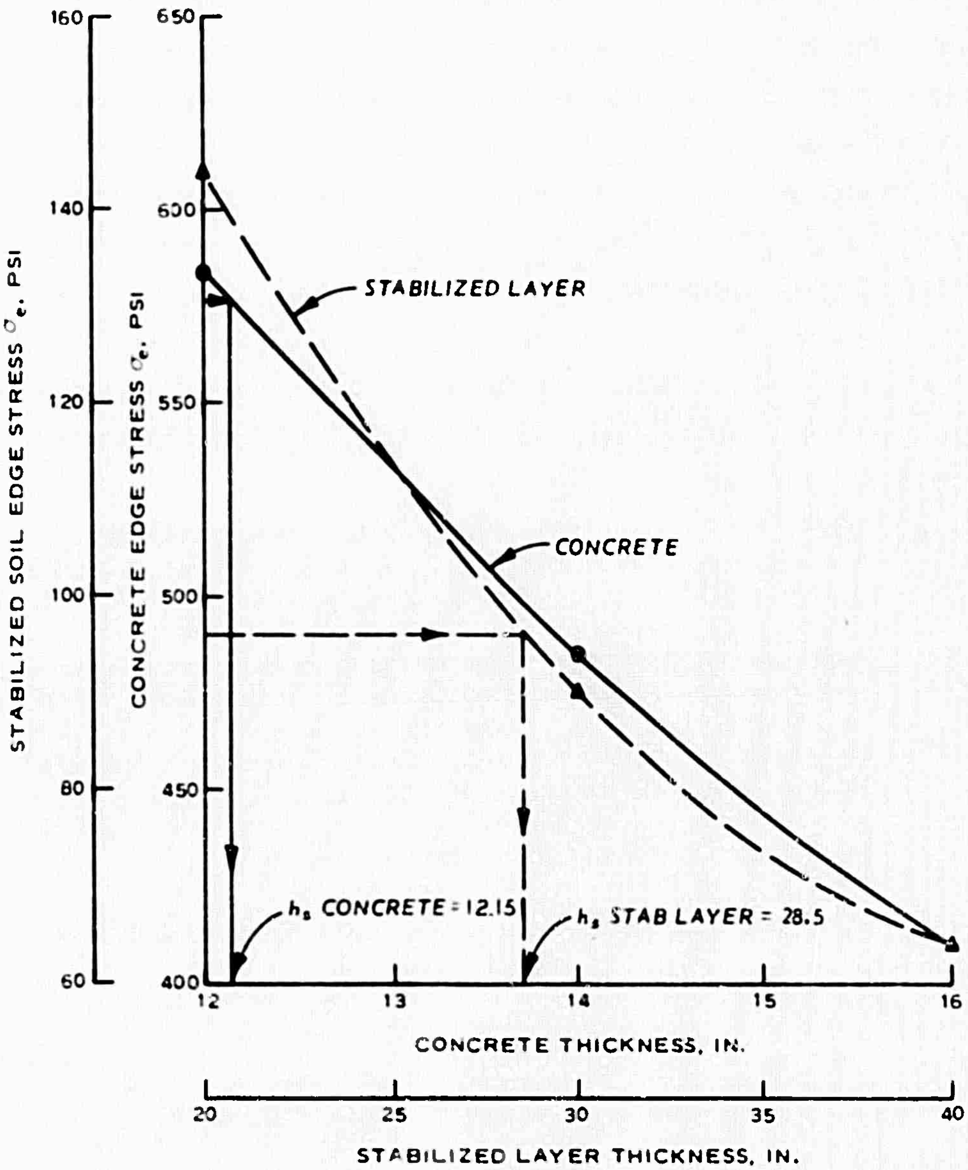


Figure 16. Determination of standard thickness for example

aircraft for rigid pavement runway ends is 3.70. Therefore, the design level of 100,000 passes will equal 100,000/3.70 = 27,027 coverages. Entering Figure 10 with this coverage level, it is found that H for plain concrete (which is also applicable to stabilized layers) is 111.2 percent. The design thickness, h_{do}, for the concrete (overlay) would then be $h_s \times H$ or $12.2 \times 1.112 = 13.6$ in. and for the stabilized layer (base pavement) h_{db} would equal $28.5 \times 1.112 = 31.7$ in.

b. These values of h_{do} and h_{db} are then used in Equation 3 to determine the required thickness of concrete (overlay), h_o, for a range of thicknesses of stabilized layer, h_b. Results are:

h_b, in.	h_o, in.
6	12.6
8	12.1
12	10.9

The final selection of stabilized layer (h_b) and concrete (h_o) should then be based on cost.

CONSTRUCTION PROCEDURES FOR STABILIZED LAYERS

The previous sections of this report have been concerned with an improved design procedure for pavement structures using stabilized layers. With the design accomplished, the proper procedures must be adhered to in the construction phase to insure that the pavement performs its intended function.

This section is devoted to those procedures and equipment necessary for proper construction of stabilized layers within a pavement system.

CONSTRUCTION PROCEDURES

Construction procedures for stabilization with lime, cement, or bituminous materials are very similar regardless of the stabilizer used. The basic requirements to obtain satisfactory construction with any of these stabilizers are to select the proper equipment to adequately pulverize the material being stabilized and to combine thoroughly and uniformly the stabilizer with the material at the proper moisture content for compaction. The three basic phases are continued below.

INITIAL SITE PREPARATION

This phase includes removal of all debris from the area to be stabilized, provision for adequate drainage, and initial grading to the required elevations and cross sections. After initial grading, any areas of unsatisfactory material should be removed and replaced with satisfactory material and the area reshaped.

PROCESSING MATERIAL

This phase consists of pulverizing the material being stabilized, thoroughly mixing the stabilizer with the pulverized material, and adjusting the moisture content of the mixture to that required for compaction.

COMPACTION AND FINISHING

This phase consists of spreading the mixture to required grade,

compacting, final grading to design grades, and curing.

One of the most important factors in stabilization construction is the scheduling of each phase so that maximum use of equipment can be maintained at all times. The initial site preparation should precede the processing of material far enough so that initial pulverizing and distributing of stabilizer and mixes may be performed at alternate locations at the same time. Compaction, finishing, and curing follow as the last steps. Construction joints should be made where each section of mixing and compaction join. Construction joints in lime- and cement-stabilized material are made by cutting back into the completed work to form a true vertical face free of loose or shattered material and beginning the next section of construction at this face. Construction joints in bituminous-stabilized materials are made by scarifying about 3 ft of the previously placed material and placing new material thereon to proper grade. If the bituminous-stabilized material has cured, a light application of the bituminous material being used should be applied to the previously placed material in the area to be scarified.

EQUIPMENT

Equipment required to construct a stabilized layer system is generally about the same regardless of the stabilizer. Heavy earthwork equipment such as bulldozers, scrapers, trucks, front-end loaders, and motor graders is necessary in the initial phase to remove debris, provide drainage, and grade to design elevations. The number of different pieces of equipment will depend on the size project and the amount of work involved with each operation.

Pieces of earthwork equipment involved in the second phase are scarifiers, pulverizers, water and stabilizer distributors, and graders. In this phase, it is also necessary to have laboratory equipment available to determine the moisture content of the mixture and truck-type scales to weigh accurately the amount of stabilizer being used if lime or cement is used as the stabilizer. Volumetric methods are used to determine the amount of bituminous material. The depth of material

to be stabilized should be considered when selecting the type of mixing equipment. Material should not be mixed or placed in compacted layers of greater than 6 in. or less than 3 in. If the required thickness of stabilized material is 6 in. or less, satisfactory stabilization can be obtained in place using rotary-type or similar mixers. If the required thickness is greater than 6 in., multiple layers must be used in order to obtain adequate mixing and compaction. Past experience has shown that in-place mixing with rotary-type equipment does not produce uniform mixing of the stabilizer with the material for the full depth of each layer when mixing on a layer that has been compacted; therefore, it is recommended that traveling plants or central-mix plants be used for multiple-layer construction.

The third phase involves equipment such as motor graders, mechanical spreaders for placing the material to the required grade and thickness, compaction equipment (sheepsfoot, rubber-tired and steel-wheeled rollers), and distributors for applying water or bituminous material for curing.

IN-PLACE CONSTRUCTION METHODS

As previously stated, this method is best suited for single-layer construction, or it can be used for the first layer of multiple-layer construction. It is generally cheaper than mixing by traveling or central-mix plants.

Individual steps for in-place stabilization using lime, cement, and bituminous materials are discussed below.

LIME STABILIZATION

Site Preparation.

a. Clear area to be stabilized and remove all debris, such as roots, stumps, and large rocks.

b. Grade area to design grade and cross section. During the original grading, drainage must be provided to prevent water from collecting or standing on the area to be stabilized. Providing adequate drainage is one of the most important steps on any construction project.

c. Remove any unsatisfactory material from the area and replace with material satisfactory for stabilization and reshape to grade. The replacement material should be similar to the adjacent material being stabilized so that the amount of lime required will not change in the area of replaced material.

d. Scarify to the depth to be stabilized. Scarification should be carefully controlled so that the subgrade beneath the layer is not disturbed.

e. Initial pulverization of the soil should be performed after scarifying to partially break down the soil prior to adding lime. If the material is a highly plastic clay and the moisture content is excessively high, initial pulverization may not be possible until lime is added and worked into the soil with equipment such as a tractor-drawn disk plow. Additional pulverization may be required.

Lime Application. Hydrated or quicklime may be applied by any of the following methods; but regardless of the method, it must be applied in a manner and in such quantities so that when uniformly mixed with the soil the specified lime content is obtained.

a. Bulk application. Mechanical spreaders or bulk trucks equipped with metering devices and spreader bars should be used for the application of bulk limes. With either type of equipment, it is important that care be taken to insure that the required amount of lime is uniformly spread over the area to be stabilized.

b. Bag application. Bags must be spaced uniformly over the area. It is recommended that bags be placed in rows both longitudinally and transversely over the area and then emptied into transverse windrows and spread. The lime may be spread with a spike-tooth harrow or by drags, or by other types of equipment, but it is recommended that spreading equipment have teeth that hold the frame above the soil to insure that the lime is uniformly spread over the area.

c. Slurry application. Since in most cases additional moisture is required to raise the moisture content of the soil being stabilized to that required for proper compaction and chemical reaction of the lime, the lime can be added in a slurry form. This slurry can be mixed in a central plant or tank truck and distributed by standard water trucks or asphalt distributors. When this method of application is used, the distributor should be followed immediately with a scarifier to mix the slurry the full depth of the layer and prevent the slurry from ponding in low places or running off into ditches. In order to apply the required amount of lime in a slurry form, it may be necessary to make more than one application of the

slurry to each layer. If more than one application is required, the scarifier should follow each slurry application.

Initial Mixing. Immediately after application of lime, the lime and soil should be partially mixed. Complete pulverization and mixing are not necessary at this time; and in cases where the soil is a heavy clay with a high moisture content, complete pulverization will be impossible. This initial mixing should be thorough enough to alleviate any dusting or adverse effects due to wetting of the lime that might be caused by wind or rainstorms. The initial mixing may be accomplished with rotary-type mixers, tractor-drawn disk harrows, or scarifiers and blades. After initial mixing, the area should be shaped to approximate grade and the surface lightly compacted to prevent excessive drying or overwetting in case of heavy rains. The lime-soil mixture should be allowed to precure for up to 48 hr before final mixing and compaction. This initial curing time allows the lime to break down the clay clods and make the mixture more friable.

Final Mixing and Pulverization. Before final mixing and pulverization are begun, the moisture content of the lime-soil mixture should be checked, and if necessary, water should be added during final mixing and pulverization. If the moisture content is more than 2 percent above optimum, the area should be aerated by turning with blade graders, disk harrows, or other suitable equipment until the optimum moisture content is within specified limits. The lime-soil mixture should be pulverized until all clods will pass a 1-in. screen and no less than 60 percent by dry weight, exclusive of plus No. 4 gravel or stone, will pass a No. 4 sieve. The lime should be uniformly mixed the full depth of the layer.

Compaction. Compaction of the mixture should begin immediately after mixing and pulverizing with sheepsfoot rollers, rubber-tired rollers, or vibratory rollers depending on the soil type. Compaction should begin at the outside edge of the area being stabilized and proceed to the center. Compaction should continue uninterrupted until the required density has been obtained. Before compaction is completed, the area should be shaped so that the design cross section will be obtained upon completion of final compaction and finishing. Final compaction and

rolling should be with multiple-wheel rubber-tired rollers and tandem-type steel-wheeled rollers.

Curing. Curing of the soil-lime mixture should begin immediately after compaction, either by moist curing or by the application of bituminous material. Moist curing can be accomplished by keeping the surface moistened by sprinkling for a period of 7 days. Curing by the application of bituminous material should be selected only for the top layer stabilized. The surface of the stabilized material should have sufficient moisture to prevent excessive penetration of the bituminous material. If the surface is not sufficiently moist, light sprinkling of the area may be necessary prior to the application of the bituminous material. Care should be taken, either by sanding or dusting the treated surface, to keep the bituminous material from being picked up by traffic.

CEMENT STABILIZATION

Many of the steps for cement stabilization are the same as for lime stabilization; therefore, details will not be given unless the procedure varies from that required for lime stabilization.

Site Preparation.

a. Clear area and remove all debris.

b. Grade area to design elevations and cross sections and provide drainage.

c. Remove any unsatisfactory material and replace with satisfactory material and reshape.

d. Scarify, pulverize, and prewet material. Prewetting will aid in pulverization if material is a dry silt or clay. Care should be taken not to scarify or pulverize below the depth to be stabilized. Pulverization should not exceed the area that can be completed in two working days.

Cement Application. Cement should not be applied if the moisture content of the pulverized material exceeds 110 percent of the optimum moisture content for the cement-treated material. Cement may be applied by either of the following methods.

a. Bulk application. Mechanical spreaders or bulk trucks equipped with metering devices and spreader bars should be used for bulk application.

b. Bag application. Bags should be uniformly spaced over the area to give the required amounts of cement, emptied into lateral windrows, and spread by rake or drag as discussed previously under lime application.

Mixing and Pulverizing.

a. Dry mixing. After application of the cement, the cement and soil should be thoroughly mixed without the addition of water. Care should be taken not to mix the cement to depths greater than required for the layer. Mixing should continue until the cement and soil are so thoroughly mixed that when water is added, the cement will not form balls. Lime may be added to reduce the plasticity index of high-PI soils and increase workability prior to the addition of cement for strength increase.

b. Moist mixing. Immediately after dry mixing, the moisture content of the soil-cement mixture should be determined; and if additional water is required, it should be uniformly applied. Equipment should be available to apply the required amount of water within 3 hr. Each increment of water should be incorporated into the soil-cement mixture to avoid excessive concentration of water at the surface of the mixture. Mixing should continue until the water is uniformly distributed throughout the full depth of the layer, with no portion of the area being undisturbed for more than 30 min. The mixture should be pulverized until all the soil-cement mixture will pass a 1-in. screen and at least 80 percent of the minus No. 4 material will pass the No. 4 sieve.

Compaction. Pneumatic-tired, steel-wheeled, or vibratory rollers should be used for compaction. Compaction should begin immediately after mixing has been completed in an area and continue as rapidly as possible so that compaction and finishing are completed before hydration of the cement. Compaction should begin at the outside edge of the area and progress toward the center. Compaction should continue until design densities are obtained over the area.

Finishing. After completion of compaction, the area should be fine-graded to conform to design elevations. Moistening of the surface may be necessary to accomplish fine grading. After fine grading has been completed, the areas should be rolled with a steel-wheeled roller.

Curing. The soil-cement mixture should be cured for a period of 7 days. Curing should begin immediately after finishing using one of the following methods:

a. Moist curing. This can be accomplished by covering the surface with straw or with burlap or cotton mats and sprinkling with water periodically to keep the surface moist.

b. Waterproof sheets. The area should be moistened with a fine spray of water and then covered with waterproof paper, polyethylene-coated burlap, or polyethylene sheeting.

c. Bituminous material. The area should be uniformly covered with bituminous material at the rate of 0.15-0.30 gal/sq yd.

BITUMINOUS STABILIZATION

Procedures for in-place stabilization with bituminous materials are very similar to those used with lime and cement except that blade-type mixing is permitted.

Site Preparation.

a. Clear area and remove all debris.

b. Grade area to design elevations and cross sections and provide drainage.

c. Remove unsatisfactory material and replace with satisfactory material and reshape.

d. Scarify, pulverize, and prewet material, if necessary. Care should be taken not to scarify or pulverize below the depth to be stabilized. Pulverization should continue until 75 percent by dry weight of the minus No. 4 sieve material passes the No. 4 sieve.

Bituminous Application. After the in-place material has been thoroughly pulverized and the required moisture content obtained throughout the mixture, the required amount of bituminous material should be distributed over the area. Bituminous distributors should be capable of applying the material at controlled rates ranging from 0.05 to 2.0 gal/sq yd and have a pressure range of 25-75 psi. If more than one pass of the distributor is needed to apply the full amount of bituminous material, partial mixing should follow each pass of the distributor.

Mixing and Pulverizing. After the required quantity of bituminous material has been applied, the soil and bituminous material should be thoroughly mixed for the full depth of the layer. Mixing may be accomplished with blade graders, disk harrows, or rotary-type mixers.

The soil-bituminous mixture should be aerated until not more than 50 percent of the original volatile material remains in the mixture. Additional blading or pulverizing may be required to speed the release of the volatile material.

Compaction. After mixing and aeration, the soil-bituminous mixture should be graded to the required cross section and grades and compacted. Compaction should begin at the outside edge of the area and progress toward the center, with rollers overlapping on successive passes at least one half the width of the rear wheel. Steel-wheeled, rubber-tired sheepsfoot, or vibratory rollers should be used for compaction. Rollers must be equipped with devices to keep the soil-bituminous mixture from adhering to the wheels or feet.

Finishing. The area should be shaped to grade as compaction is being completed and final-rolled with a rubber-tired or steel-wheeled roller. After rolling has been finished, the area should be given an application of bituminous material for waterproofing.

TRAVELING PLANT METHOD

The traveling plant method can be used either for mixing in-place material or for mixing borrow material on the area being stabilized. The traveling plant method or the central-mix plant method, which will be discussed later, is recommended when more than one layer of stabilized material is necessary. Traveling plant mixers are available that will combine water, stabilizer (lime, cement, or bituminous material), and soil in one operation. With windrow-type traveling plant mixers, windrows must be uniform and have sufficient material to cover a predetermined width of area to be stabilized to the required compacted thickness. When traveling plant mixers are used, site preparation is the same as when in-place mixing equipment is used. After the site has been prepared and the subgrade graded to design elevations and cross sections, the material for the first lift is placed in a uniform windrow, the moisture content determined (so that the amount of water to be added is known), and then the material is mixed and the required amount of stabilizer and water added during the mixing operation. It is important

that the traveling plant move at a uniform rate of speed so that a constant amount of water and stabilizer can be added as the mixer travels along windrows.

After mixing, the mixture should be spread over the predetermined area to the design cross section and compacted. Compaction, finishing, and curing of the material should be as previously described for lime-, cement-, or bituminous-stabilized material under in-place construction.

CENTRAL-MIX PLANT METHOD

The central-mix plant method is particularly adaptable to large projects with multiple layers where borrow material is used. The plant should be located near the project site, with adequate area available for storage of each gradation of material. Arrangement of the storage areas should be such that foreign material is not mixed into the stockpiles.

SITE PREPARATION

Areas to be stabilized should be clear of all debris and graded and compacted to the elevations and cross sections required for the subgrade. During the grading operation, all unsatisfactory material should be removed and replaced. Drainage should be provided to eliminate any water from collecting on areas where stabilized material is to be placed.

MIXING AND SPREADING

The plant must be capable of producing a uniform mixture of the stabilizer (lime, cement, or bituminous material) and water, if required, with the selected material. For cement stabilization, it is recommended that the material and cement be dry-mixed first to eliminate balls of cement, that water then be added, if required, and mixing completed. For lime or bituminous stabilization, water, if required, may be added along with stabilizer.

Mechanical spreaders can be used for spreading either of the mixtures. Prior to spreading mixtures with lime or cement, the subgrade

or course on which the mixture is being placed should be thoroughly moistened. Moistening is not necessary for bituminous-stabilized layers.

COMPACTION, FINISHING, AND CURING

Compaction, finishing, and curing of the mixtures should be as previously described for each of the materials under in-place construction.

SUMMARY

The comparative performance of full-scale structural layers stabilized with bitumen, cement, or lime indicated that a reduction of conventional flexible or rigid pavement thickness requirements is warranted when using high-quality stabilized layers. A design procedure for flexible and rigid airport pavement utilizing soil stabilization is presented which quantifiably predicts required airport pavement thicknesses.

Construction procedures for stabilized pavement systems based on actual field operations are also presented. Types of equipment to combine soil-additive mixtures adequately and techniques for compaction, finishing, and curing are presented.

RECOMMENDATIONS

As a result of this study, the following recommendations are made:

a. Use the design procedures presented herein to develop thickness design criteria for flexible and rigid pavements containing stabilized soil layers.

b. Make appropriate revisions to References 5 and 6 incorporating revised equivalency factors.

c. As theoretical design procedures become more developed, reanalyze all available data on stabilized soil layers in pavement systems.

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APPENDIX A: THEORETICAL ANALYSIS OF AC-SURFACED ITEMS

The use of computerized analytical models in analyzing the performance of flexible pavement systems has received widespread acclaim, and such models are viewed as a key element in the development of an improved design procedure. A number of techniques have been employed in the models, and several programs are available for computing the required pavement response parameters. The major techniques are discussed in detail in AFWL-TR-69-9.[23]*

For this portion of the analysis, two programs were used. The first and principal program, CHEVRON, was developed by the California Research Corporation.[24] This program uses Burmister's layered elastic theory to compute stresses, strains, and displacements in a closed-form solution, and it has been modified at WES to handle multiple-wheel gear loadings by use of the superposition principle. The other program, FEPAV, is a finite element program which was obtained from the University of California at Berkeley. This program can handle nonlinear soil properties but is limited to use with single-wheel loads.

METHOD 1

Preliminary work for this part of the theoretical analysis was accomplished prior to traffic testing and involved the selection of the loads to be applied in lanes 1 and 2 (Figure 1). In this work, performance criteria were established based on computed subgrade stresses and surface deflections. The general approach for the computations and the basic data are presented in Barker et al.[25] Data from the related studies reported by Grau[2] and Burns et al.[3] were also used in establishing the criteria, particularly those data for twin-tandem traffic on the items containing stabilized layers. The criteria established are presented in Figures A1 and A2, in the form of coverages as a function of subgrade stress and coverages as a function of surface deflection. The modulus values required to produce pavement response compatible with measured response for the four AC-surfaced items were estimated based

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* These refer to references in the main text.

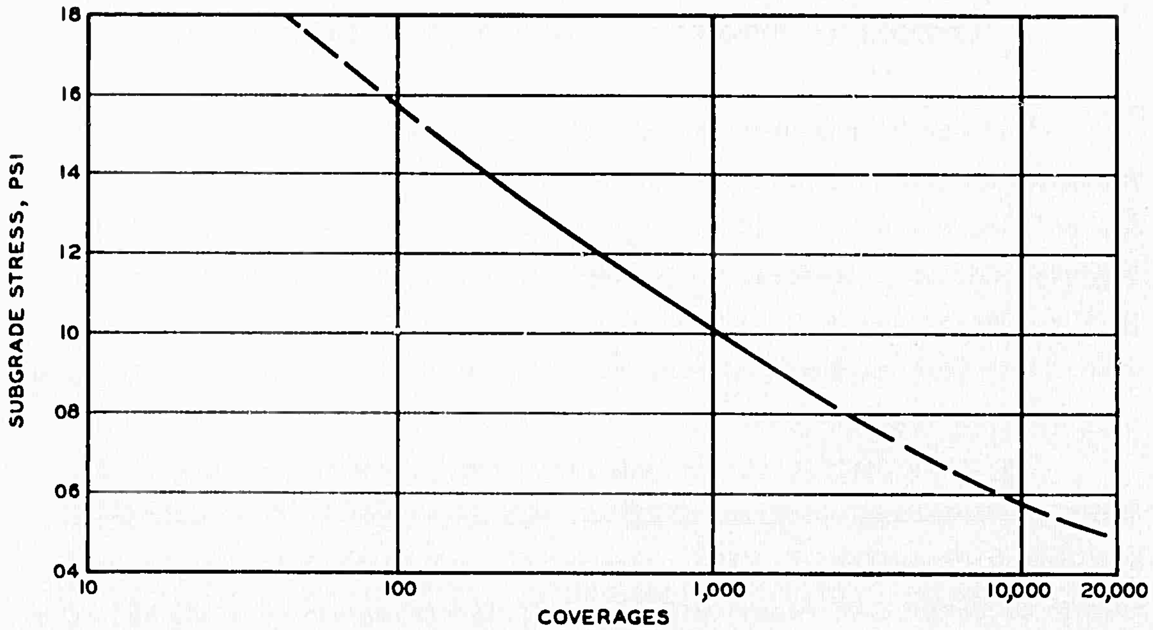

Figure A1. Relationship between subgrade stress and coverages

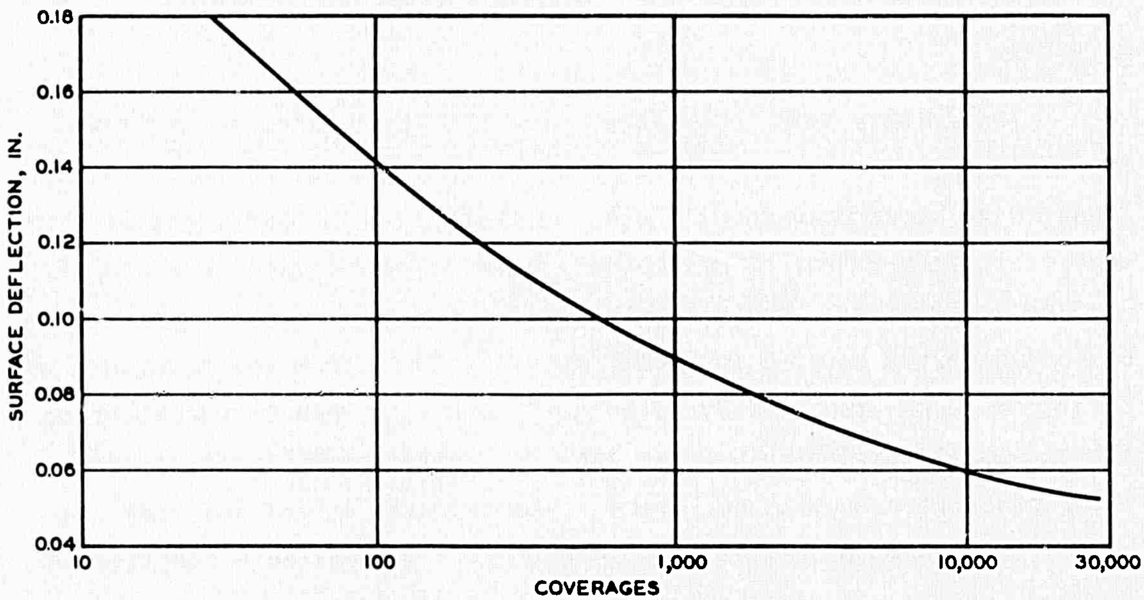

Figure A2. Relationship between surface deflection and coverages

on data presented in the literature, from results of unconfined compression and resilient triaxial tests, and from parametric studies of the test section. The most heavily weighted data were those reported by Grau[2] for the test section containing cement- and lime-stabilized layers. In the evaluation of this test section, modulus values of 20,000, 40,000, 100,000 psi were used for the lime-stabilized lean clay (CL, E-7),* cement-stabilized lean clay, cement-stabilized clayey gravelly sand (SP-SC, E-5), respectively.

The relationships shown in Figures A1 and A2 were then used to predict the pavement performance for different loads. Since items 2, 3, and 4 were the same except for the stabilized base course material (see Figure 1), relationships between the modulus values and the predicted number of coverages were developed for different loadings. The relationships developed from the surface deflection criteria are shown in Figure A3, and those developed from the subgrade stress criteria are shown in Figure A4. During the development of these criteria, 40,000 and 100,000 psi were estimated as modulus values for cement-stabilized lean clay and cement-stabilized clayey gravelly sand, respectively; therefore, these values were used for items 2 and 3 since the stabilized materials were similar. However, no material similar to the stabilized base of item 4 had been tested, so the modulus of this material had to be estimated by comparing it with that of other materials on the basis of laboratory tests. The preliminary results of tests conducted on field-mixed laboratory samples obtained from the test section are presented in Table A1. The data in Table A1 show that the cement-stabilized gravelly sand (SP, E-1) is consistently stiffer than the cement-stabilized clayey sand (SC, E-7). From the values of the resilient modulus and the tensile modulus, the stabilized clayey sand appears to be stiffer than the stabilized lean clay, while from the values of the compressive modulus, the stabilized lean clay appears to be stiffer.

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* Throughout this Appendix, the first soil classification designation in parentheses indicates the classification according to the Unified Soil Classification System (USCS).[26] The second designation indicates the Federal Aviation Administration (FAA) soil classification.[27]

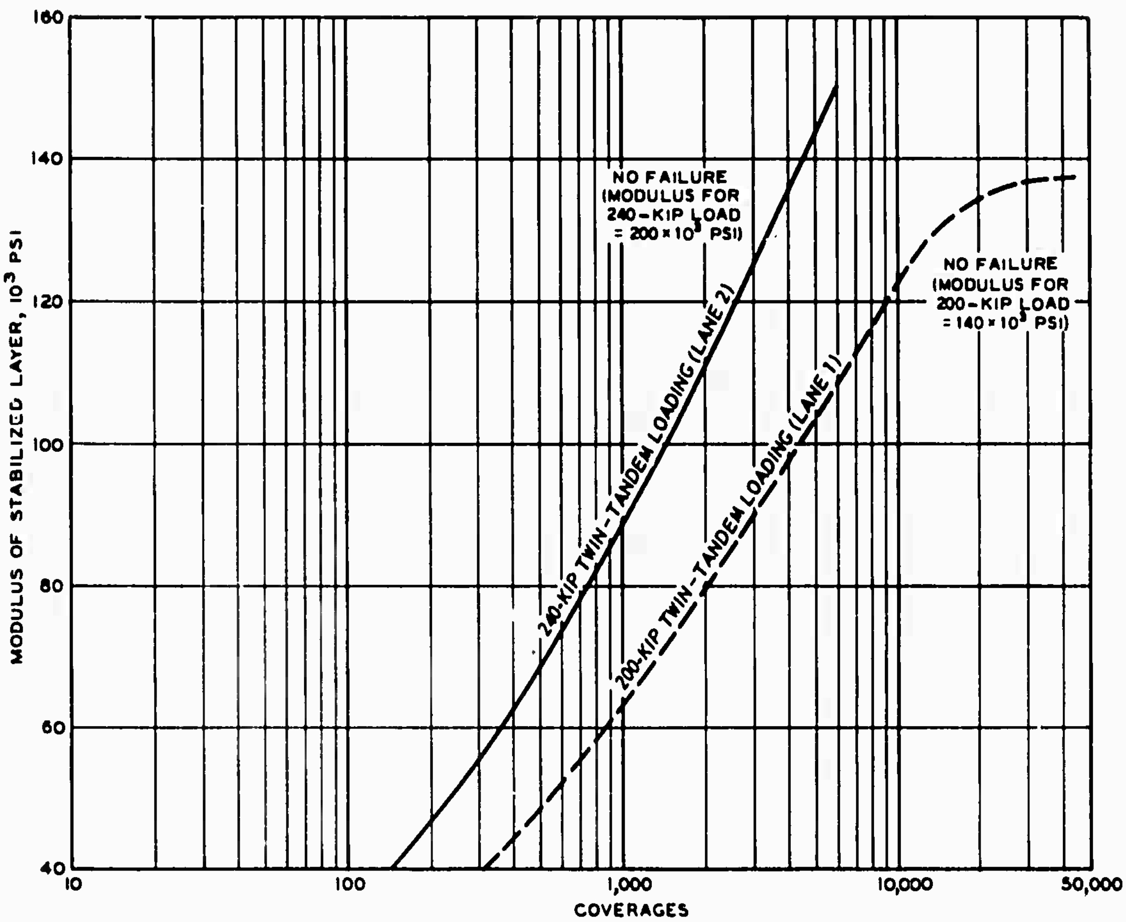

Figure A3. Relationships between stabilized layer modulus and coverages for items 2-4 developed from surface deflection criteria

Figure A4. Relationships between stabilized layer modulus and coverages for items 2-4 developed from subgrade stress criteria

Table A1

Results* of Laboratory Tests of Stabilized Materials of Items 1–4 of the Flexible Pavement Test Section

Item No.	Material	Stabilizing Additive	Average Resilient Modulus M_R 10^3 psi	Average Modulus from Unconfined Compression Test E_C 10^3 psi	Average Modulus from Indirect Tensile Test E_T 10^3 psi	Average Unconfined Compressive Strength Q_u psi	Average Indirect Tensile Strength S_t psi
1	Lean clay (CL, E-7)	3 percent lime	115	30	49	147	14
		2 percent portland cement					
		10 percent fly ash					
2	Lean clay (CL, E-7)	12 percent portland cement	140	79	36	455	40
3	Gravelly sand (SP, E-1)	5 percent portland cement	--	100	452	630	90
4	Clayey sand (SC, E-7)	5 percent portland cement	180	37	68	190	39

* At 28-day cure.

On the basis of the comparison of the resilient and tensile moduli, the modulus of the base of item 4 was estimated as 60,000 psi. The stabilized lean clay of item 1 was judged in a similar manner to be less stiff, and the modulus was estimated as 30,000 psi. The modulus of the crushed limestone (SW-SM, E-1) of item 1 was assumed to be 60,000 psi (twice the modulus of the stabilized lean clay base). A modulus value of 50,000 psi was used for the AC surfacing of all four items. Poisson's ratio was assumed to be 0.3 for the stabilized and granular materials and 0.5 for the AC and the subgrade materials.

Based on this preliminary analysis of the test section, the coverage levels presented in Table A2 were predicted. The performance predicted for the 200-kip loading more nearly agreed with the desired traffic levels than did the performance predicted for the 240-kip loading, so the 200-kip loading was chosen for trafficking lane 1. The loading for lane 2, to be chosen based on results of the tests of lane 1, was 240 kips.

Table A2 also shows the actual number of coverages applied to the test section. The predicted coverages were generally lower than the actual coverages for lane 1 and higher for lane 2. This trend indicates that performance is much more sensitive to load increases than was indicated by the predictions. Such apparent sensitivity to load could be due to a number of factors. The first would be differences in material properties of lane 1 and lane 2. It was noted in Volume I that considerable variation in cement content existed within the stabilized layers. Although there are no data indicating such, it is possible for the stabilized layer of lane 2 to be weaker than the stabilized layers of lane 1. A more likely reason for the apparent sensitivity to load would be the difference in subgrade strengths of lane 1 and lane 2. From Volume I it is seen that the noted CBR values for lane 1 were 5.6, 5.4, 3.8, 4.9, and 4.0 for items 1, 2, 3, 4, and 5, respectively, and for lane 2 were 4.4, 4.0, 3.2, 5.2, and 4.2 for items 1 2, 3, 4, and 5, respectively. In addition to possible differences in strength the material could behave nonlinearly with respect to load;

Table A2

Comparisons of Predicted and Actual Coverages for Lanes 1 and 2 of the Flexible Pavement Test Section

	200-kip Assembly Loading (Lane 1)			240-kip Assembly Loading (Lane 2)		
	Predicted Coverages Based on Cited Criterion			Predicted Coverages Based on Cited Criterion		
Item No.	Surface Deflection	Subgrade Stress	Actual Coverages	Surface Deflection	Subgrade Stress	Actual Coverages
1	1000	2500	3660	300	1500	600
2	330	1000	3600	140	500	340
3	5000	5200	7820	1400	2600	620
4	900	2000	1380	360	1000	120

i.e., an increase in load could produce an increase in pavement response not proportional to the increase in load. Later plate tests indicate that the pavement does in fact behave nonlinearly. Another possibility which must be faced is that the criteria used do not in fact represent the true relationship between pavement response and pavement performance.

METHOD 2

During the past year limiting subgrade strain criteria (Figure A5) have been developed for predicting the performance of flexible airport pavements. These criteria were developed employing a finite element program for analysis of conventional flexible pavements.[28] In the development of the criteria the modulus of the granular material was characterized as a function of the first stress invariant. To predict the performance of the test sections, a modulus is assigned to the layers, the subgrade strain is computed by the use of an analytical model, and from the relationship in Figure A5 the coverage level to failure is determined.

COMPARISON OF METHODS 1 AND 2

Items 2-4 were used as the basis for comparisons between methods 1 and 2. The comparisons were made by considering the base modulus values that would be necessary to predict the actual coverages. Since the second method employs vertical strain as the response parameter for predictions, the relationships between the base modulus and the vertical strain at the top of the base and at the top of the subgrade were developed for both the 200- and the 240-kip loadings. These relationships are shown in Figure A6. For these items the strain at the top of the base for base modulus values lower than 80,000 psi would be greater than the strain at the top of the subgrade. In the development of the relationships between base modulus values and coverages, the larger of the two strains was allowed to control. From the relationships shown in Figures A3-A6, relationships between base modulus values and coverages were develcped for the 200-kip loading (Figure A7) and 240-kip loading (Figure A8). By entering these curves with the actual

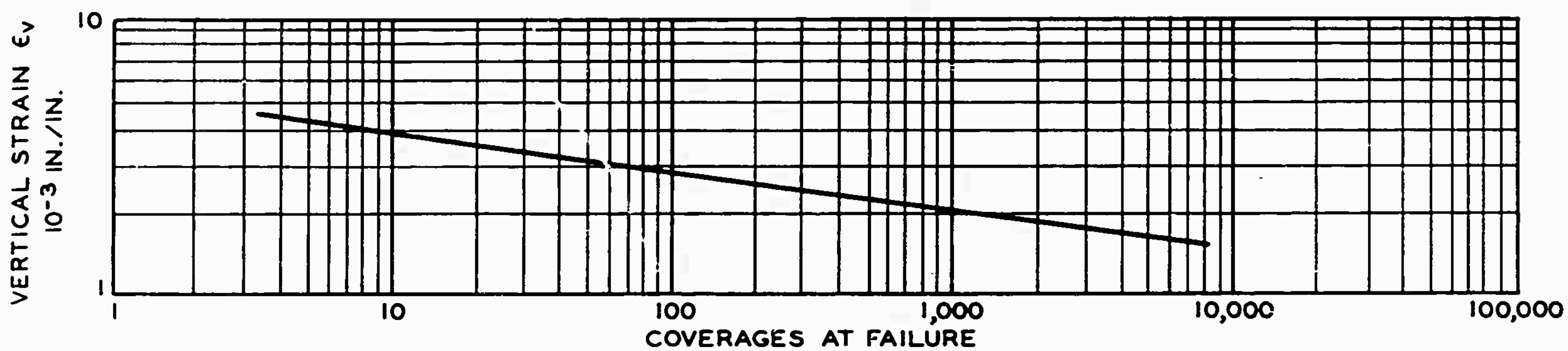

Figure A5. Relationship between vertical strain at the top of the subgrade and performance for conventional flexible pavements under multiple-wheel loads

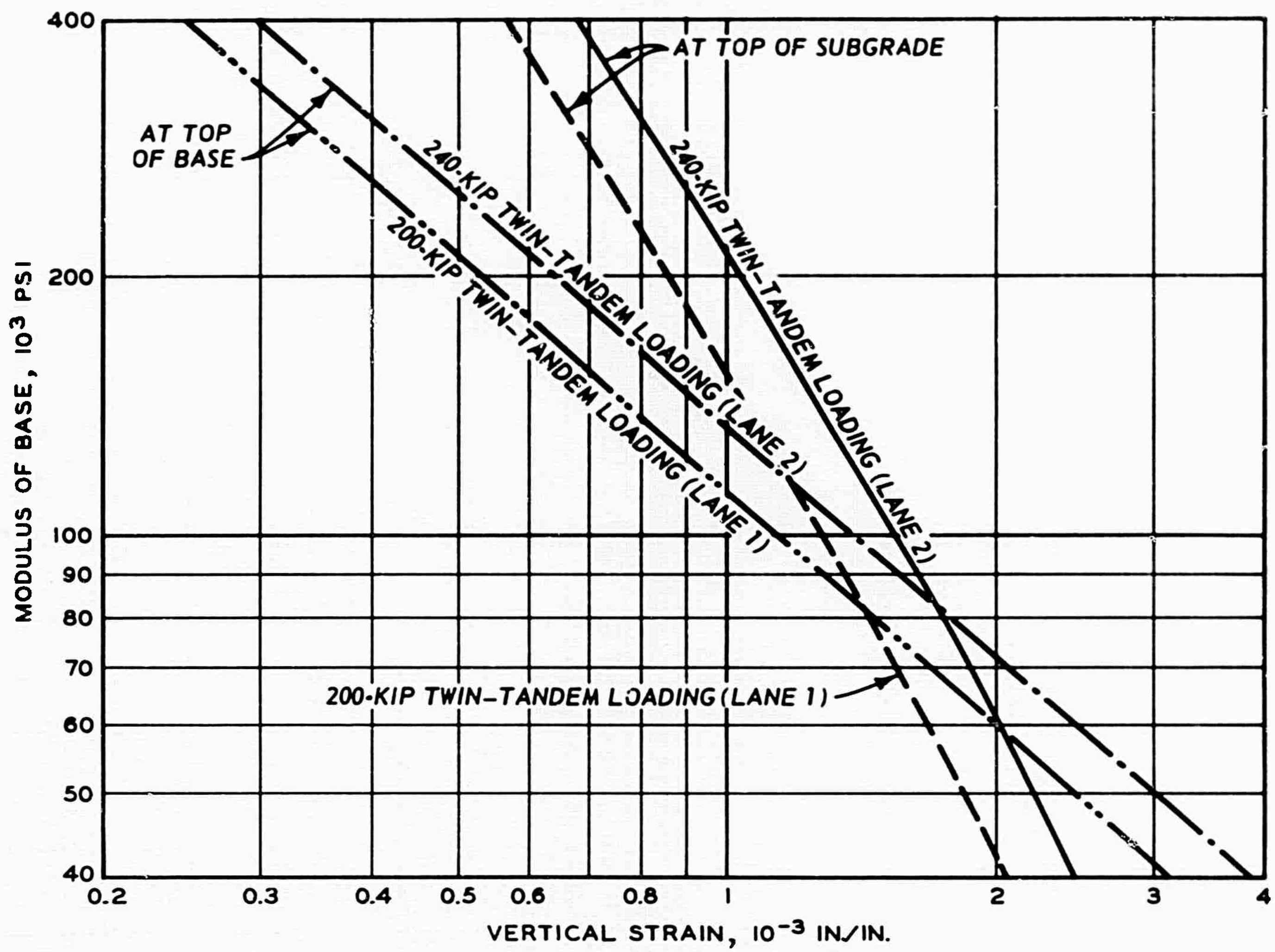

Figure A6. Relationship between base modulus and vertical strain at the top of the base and the top of the subgrade

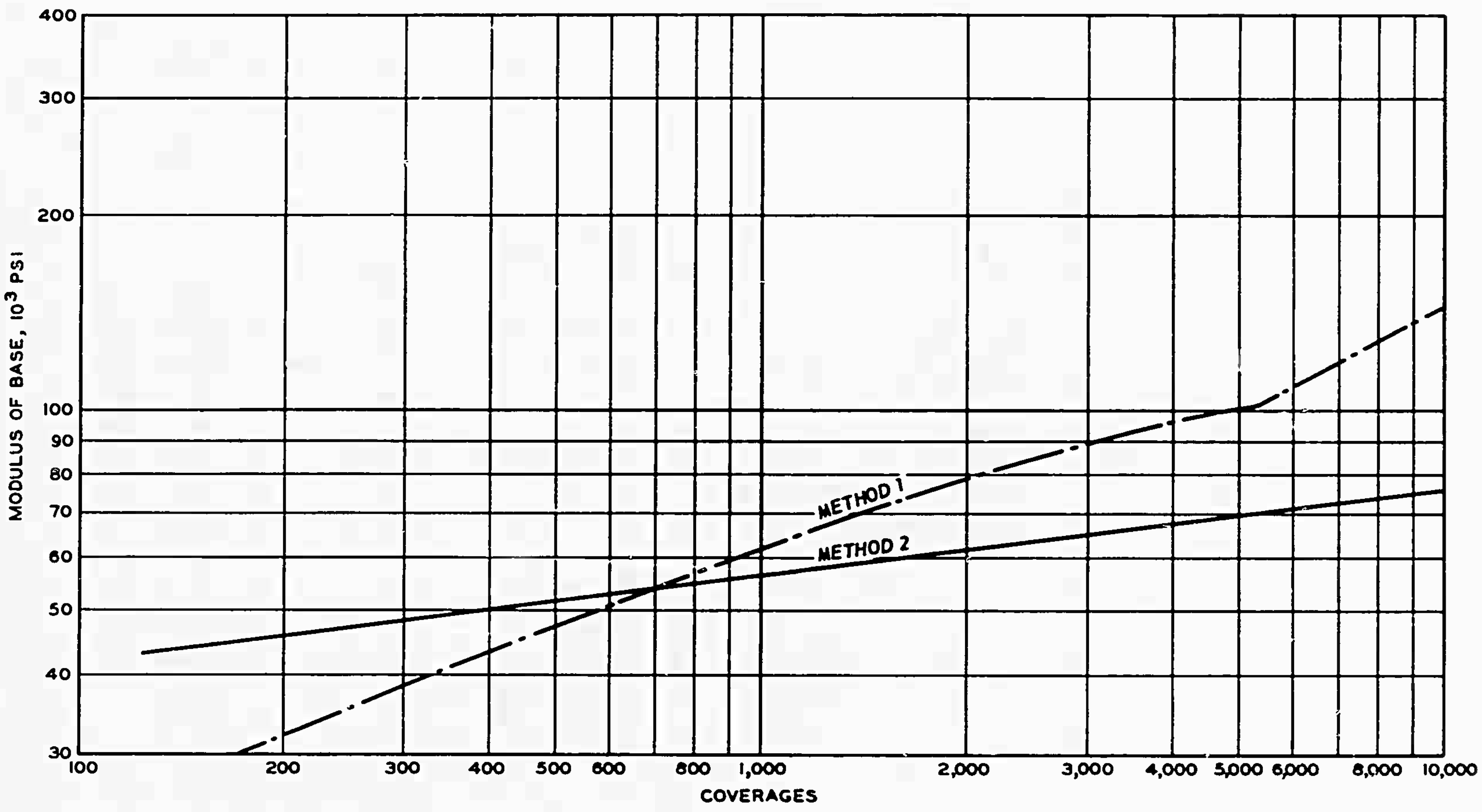

Figure A7. Relationship between base modulus and coverages for 200-kip twin-tandem loading

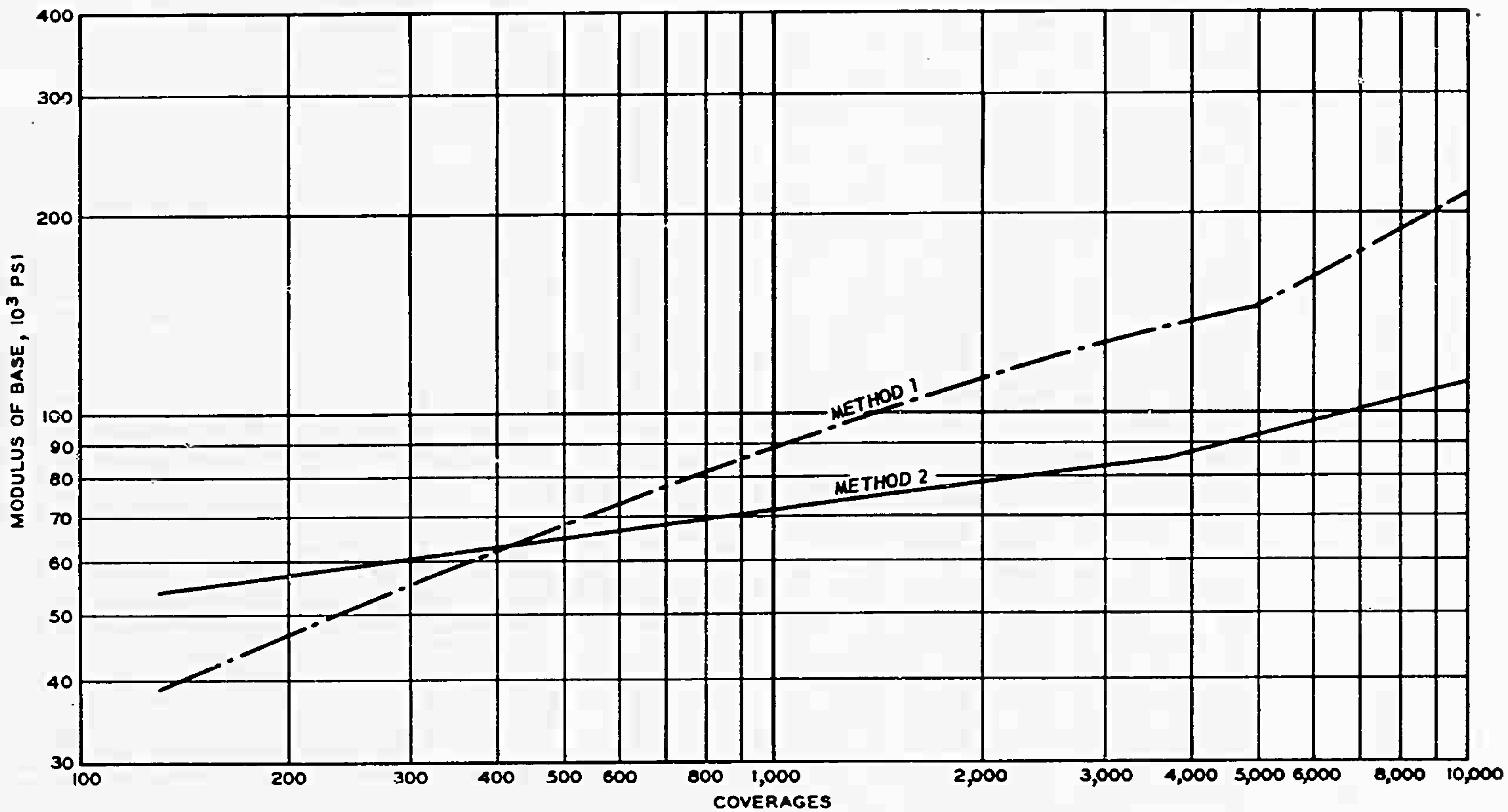

Figure A8. Relationship between base modulus and coverages for 240-kip twin-tandem loading

number of coverages, the base modulus required can be determined. These required modulus values are presented in Table A3. From these data, it appears that performance is much more sensitive to load than is indicated by either of the two methods.

PLATE LOAD TESTS

To determine the response of the pavement items to load, a series of tests was conducted in which the pavement deflections were measured at different levels of a repeated plate loading. The loading equipment and the instrumentation for measuring the pavement deflection are shown in Figure A9. The load curves generated with this equipment are shown in Figure A10. It should be noted that the elastic deflections of items 2 and 4 were greater than those of items 1 and 3, and that items 2 and 4 performed the poorest. Also, for item 4, the rate of deflection was increasing with increasing load, indicating a nonlinear material response to loading.

These data were next used to check the estimates of the apparent modulus of the base for items 2-4. For this analysis, a finite element technique was used to predict deflection for base modulus values of 50,000 and 100,000 psi. The material properties used as input were slightly different from those used in the previous analysis. Since all of the plate tests were conducted during cold weather and a nonlinear characterization was employed for the processed subgrade, a modulus of 300,000 psi was used for the AC surfacing. The computed surface deflections are compared with the measured surface deflections in Figure A11. From this comparison, it can be seen that the deflection basin computed using the 50,000-lb base modulus more closely follows the measured deflection basins than did the two basins computed using the 100,000-psi base modulus. It appears, therefore, that the apparent resilient base modulus for item 3 is between 50,000 and 100,000 psi, whereas the apparent resilient base moduli for items 2 and 4 are lower than 50,000 psi. Thus, the plate loading tests confirm the low modulus values indicated in the previous analysis.

Table A3

Comparisons of Required Base Modulus Values for Items 2-4 of Lanes 1 and 2 of the Flexible Pavement Test Section

Item No.	Required Base Modulus, psi for 200-kip Loading (Lane 1) Method 1	Method 2	Required Base Modulus, psi for 240-kip Loading (Lane 2) Method 1	Method 2
2	94,000	67,000	56,000	61,000
3	125,000	74,000	75,000	67,000
4	70,000	58,000	38,000	53,000

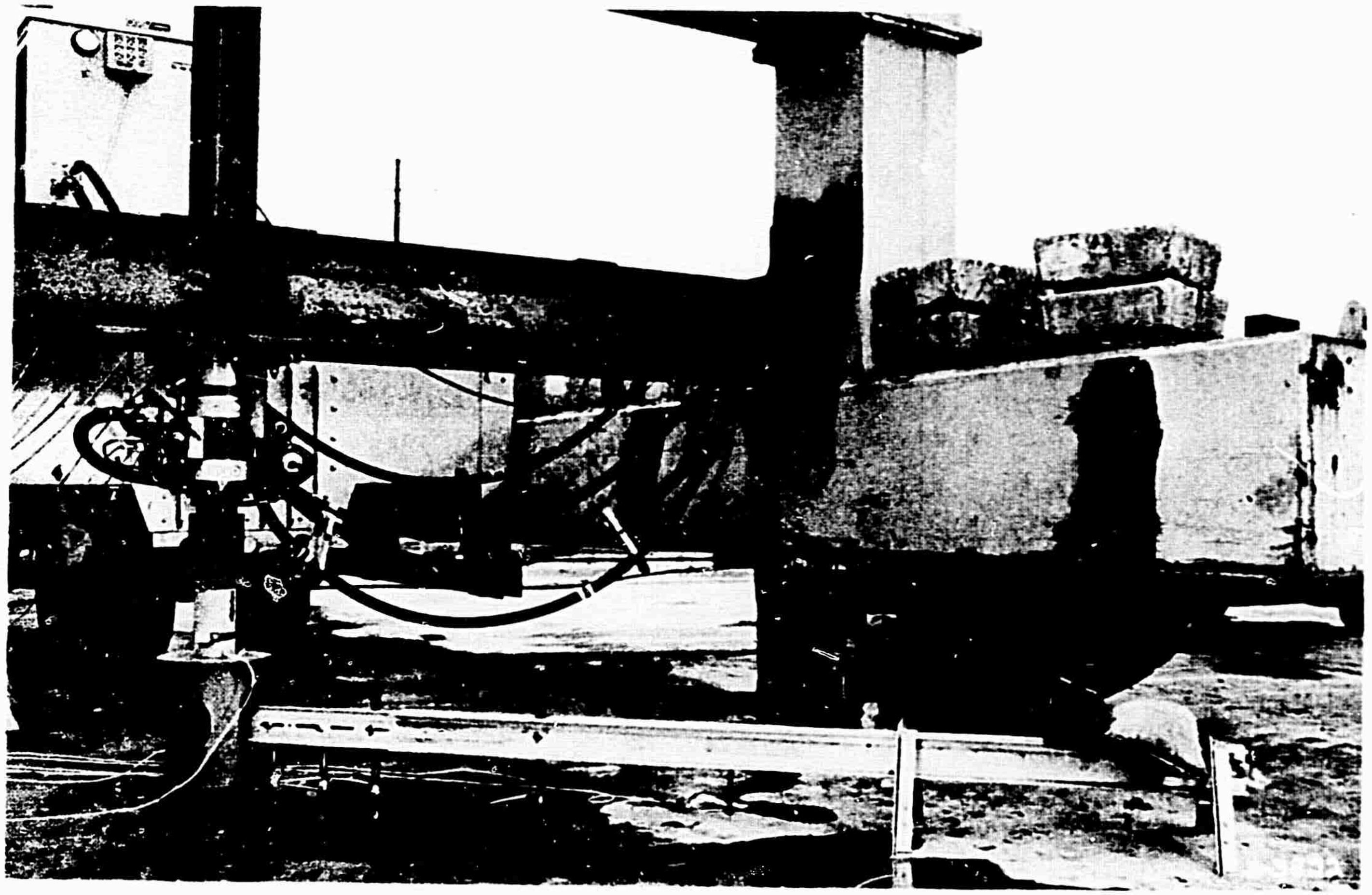

Figure A9. Loading equipment and instrumentation for pavement deflection tests

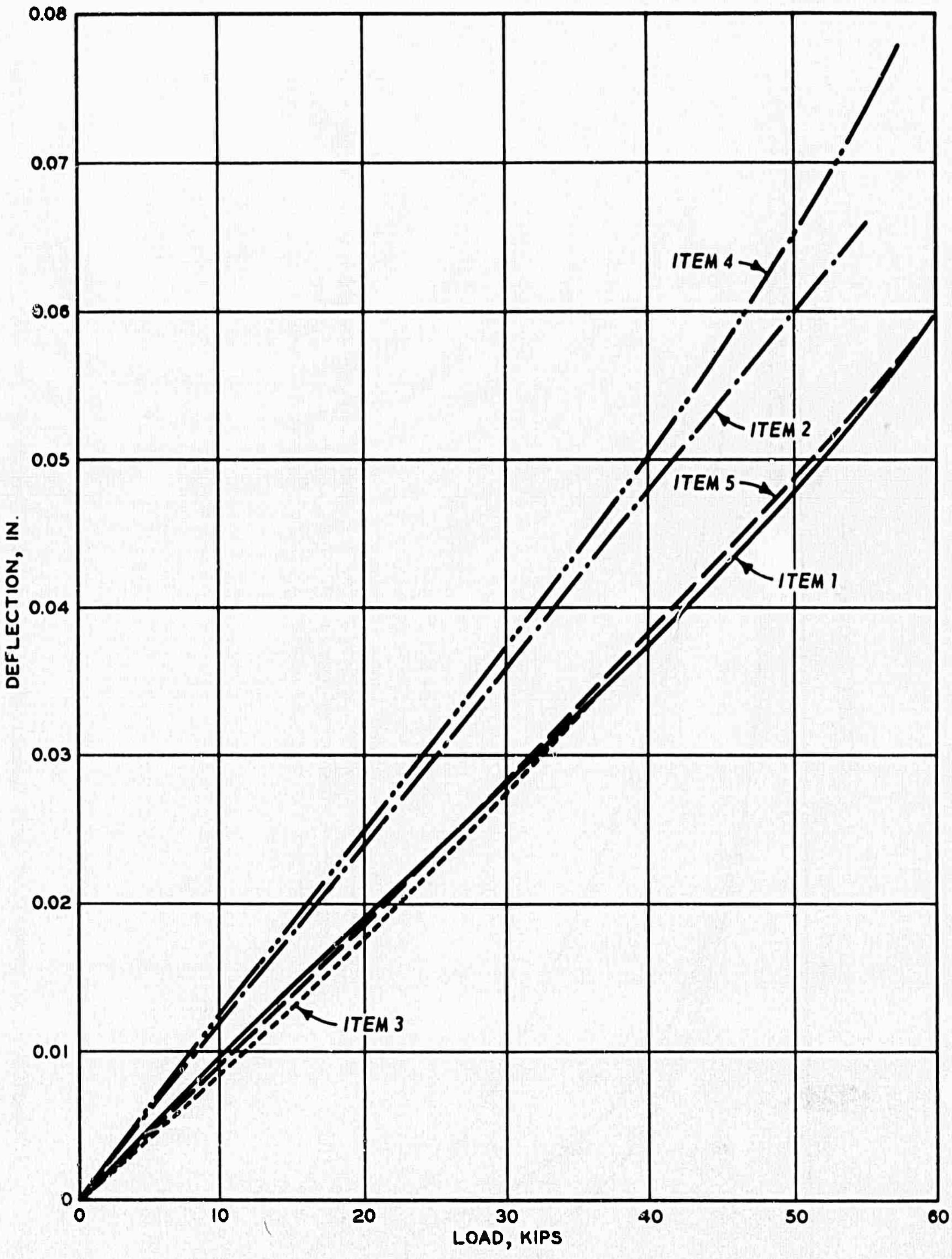

Figure A10. Deflection-load curves generated from repeated plate loading tests

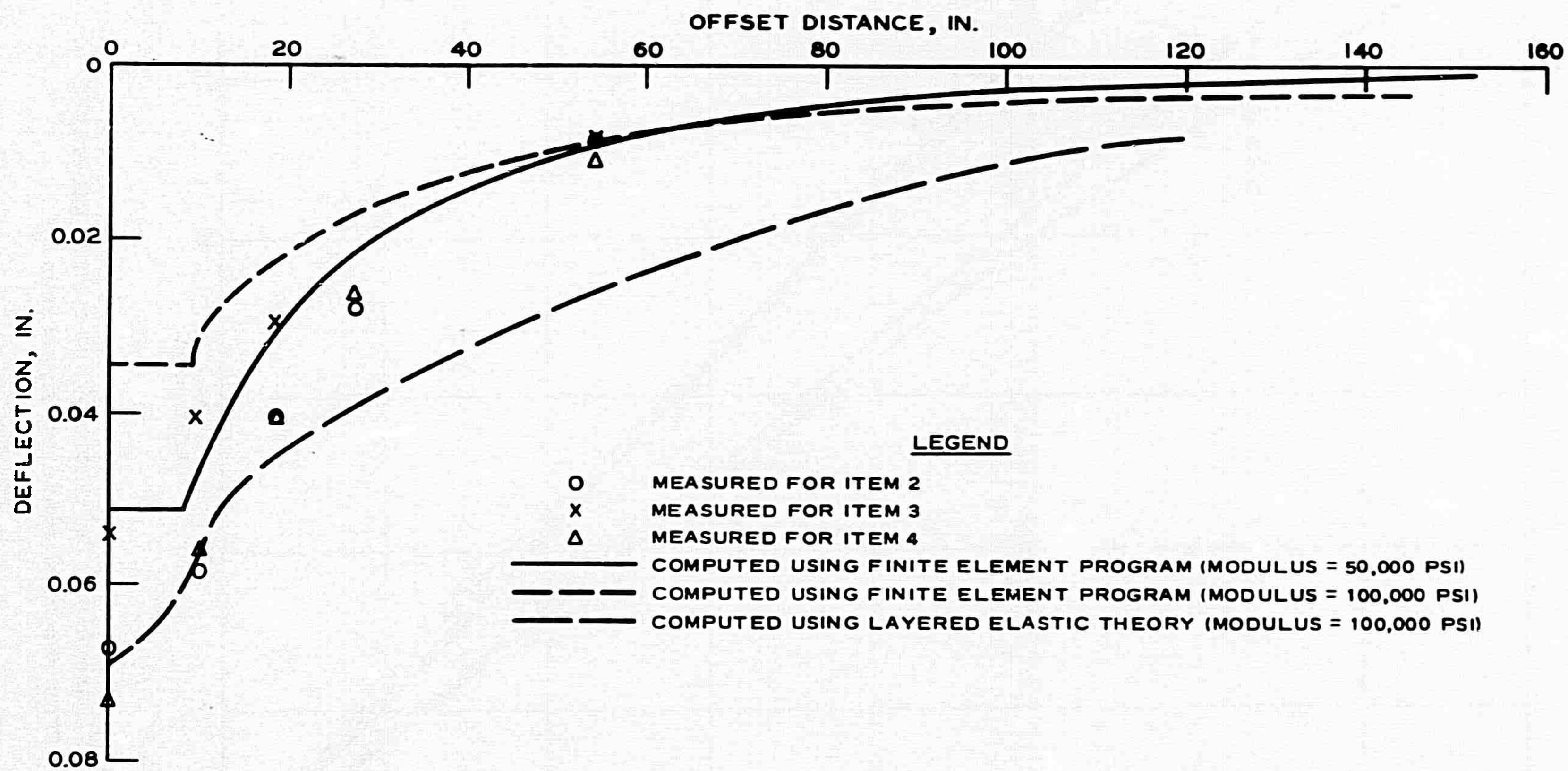

Figure A11. Comparison of computed and measured surface deflections for 50-kip plate loading

For each item, at least one series of plate tests was conducted over a set of Bison coils.[2] The readings for item 2 were invalidated due to a misplaced Bison coil. Comparisons between the measured subgrade strain for the other items and the computed subgrade strain are shown in Figure A12. The nonlinear behavior of the subgrade is apparent from both the measured curves and the computed curves. For item 3 (the only item for which the load was carried to a full 60 kips), the nonlinear behavior becomes evident between 50 and 60 kips. This development, as mentioned earlier, may in part explain the tremendous differences in the performance under the 200- and 240-kip loadings.

Thus far, reference has been made only to the resilient response; however, as was noted in the performance data, the permanent deformation under traffic can lead to pavement failure long before the pavement fails due to surface cracking. In the plate load tests, large permanent deformations were recorded.

DISCUSSION OF THEORETICAL ANALYSIS

The theoretical approach to pavement analysis was applied to the selection of the initial traffic load. The decision to reduce the initial traffic load from the 240-kip design load to the 200-kip load proved to be a sound decision and indicated the value of a theoretically based analysis. It has been shown in this section that with proper material characterization, correlations can be developed between computed response parameters and pavement performance. It has also been shown that the stiffness of the stabilized layers was considerably lower than the resilient stiffness as determined by testing of laboratory prepared specimens. The apparent stiffness of the field material did agree closely with the stiffness as measured in the unconfined compression test, but such agreement is considered coincidental. The low stiffness measured in the field test is believed to be due primarily to construction variability, curing and cracking, and the inherent differences between field and laboratory materials. The transfer from laboratory material characterization to actual field material properties

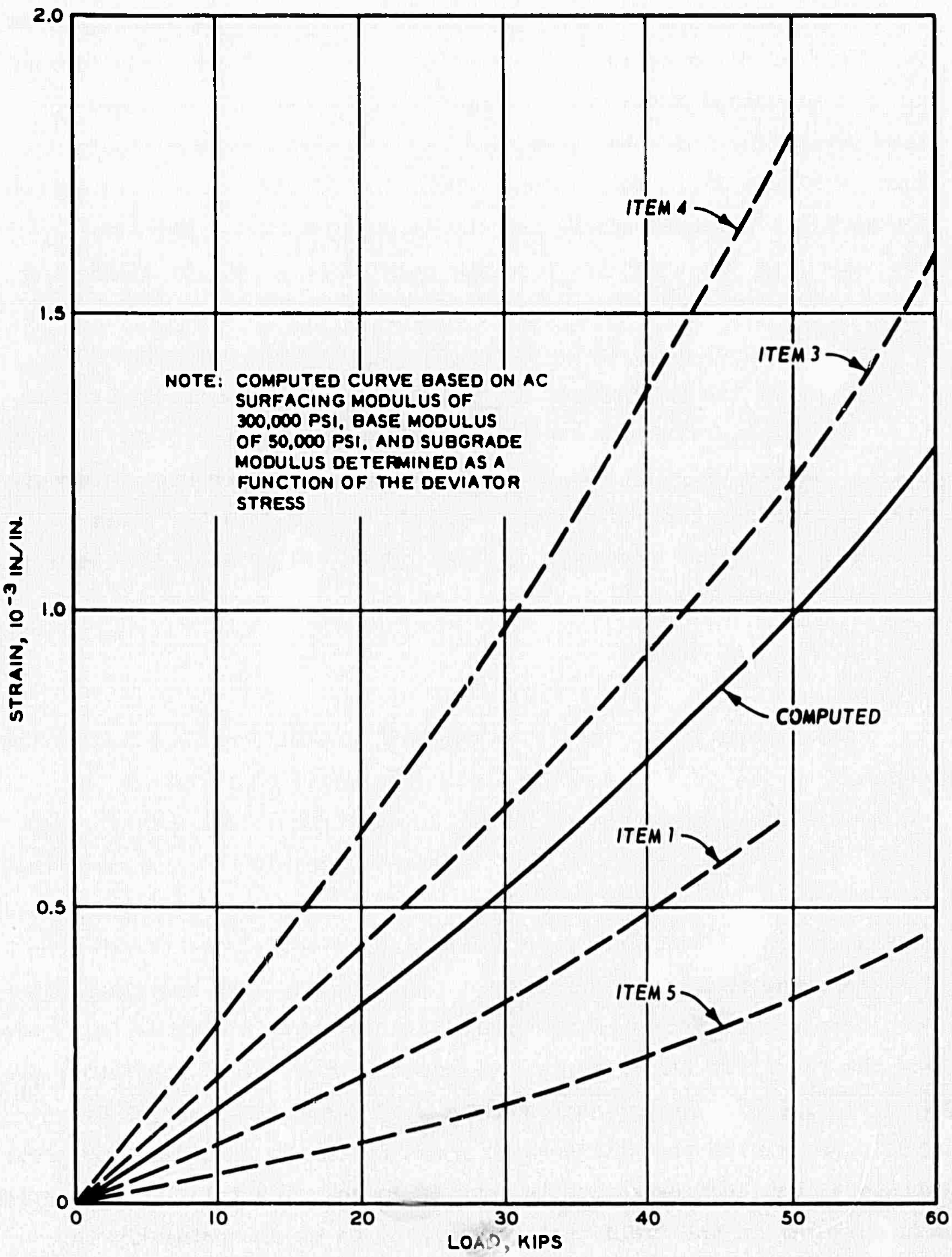

Figure A12. Comparison between computed and measured subgrade strain

is considered to be the major obstacle in the development of a theoretically based design procedure. At this time such a transfer is not possible and thus a strictly theoretically based design procedure cannot be perfected. This is not to say, however, that the data presented cannot be used in an analysis of flexible pavement having stabilized layers, provided competent engineering judgment is used in the selection of both the criteria and the design stiffness of the stabilized layers nor that a more rational procedure cannot be developed which would be an improvement in the design of flexible pavement. Such a procedure is to require considerable effort in understanding the basic response and behavior of pavement systems containing stabilized layers and for the development of empirical data necessary to produce a reliable design system.

APPENDIX B: PROCEDURES FOR DETERMINING FLEXURAL STRENGTH AND MODULUS OF ELASTICITY OF BITUMINOUS CONCRETE

LABORATORY TEST METHOD

SCOPE

These procedures describe preparation and testing of specimens of bituminous concrete to determine flexural strength and modulus of elasticity. The procedures are an adaptation from tests conducted on portland cement concrete (PCC) specimens.

APPLICABLE STANDARDS

The following standards are applicable to this procedure:

a. ASTM C 78, "Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading)."

b. CRD-C 21-58, "Method of Test for Modulus of Elasticity of Concrete in Flexure."

APPARATUS

The following apparatus are required: Testing machine capable of applying repetitive loadings for compaction of beam specimens 6 by 6 by 21 in. to the design density. (An Instron electromechanical testing machine meets this requirement.) A steel mold, suitably reinforced to withstand compaction of specimens without distortion; two Schaevitz-type 2000 HR LVDT's; a 5000-lb load cell; an X-Y recorder; and a testing machine for load applications conforming to ASTM C 78. (A Baldwin or Tinius Olsen hydraulic testing machine is suitable for this purpose.)

MATERIALS

Sufficient aggregate and bitumen meeting applicable specifications to produce six 6- by 6- by 21-in. test specimens are required. In the event the proportioning of aggregate and bitumen, bitumen content and density of compacted specimens are not known, additional materials will be required to conduct conventional Marshall tests to develop the needed mix design data.

SAMPLE PREPARATION

Prepare in a laboratory mixer four portions of paving mixture for one 6- by 6- by 21-in. beam test specimen consisting of aggregate and bitumen in the proportions indicated for optimum bitumen content. Total quantity of paving mixture should be such that when compacted to a uniform 6- by 6-in. cross section, the density of the beam will be as specified from previous laboratory mix design tests or other sources. Temperature of the paving mixture at time of mixing should be such that subsequent compaction can be accomplished at 250°F ± 5°F. Place two of the four portions in the 6- by 6- by 21-in. reinforced steel mold and compact to a 3-in. thickness with a 6- by 6-in. foot attached to the repetitive loading machine. Shift the mold between load applications to distribute the compaction effort uniformly. Add the remaining two portions and continue compaction until the paving mixture is compacted to exactly a 6- by 6-in. cross section. After compaction, place a 6- by 21-in. steel plate on the surface of the paving mixture and apply a leveling load of 2000 lb to the plate. Prepare six beam test specimens in the manner described.

After cooling, remove the beams from the molds and rotate 90° so that the smooth, parallel sides will become the top and bottom. Cement an "L"-shaped metal tab with quick-setting epoxy glue to each 6- by 21-in. side of the beams on the beams' neutral axis at midspan. The tabs should be drilled for attachment of the LVDT's. Cure the beams at 50°F for four days prior to testing.

TEST PROCEDURES

Condition three specimens each at 50°F and 75°F for at least 12 hours prior to testing. (If testing occurs immediately after curing the specimens at 50°F for four days, no additional conditioning is required for the specimens tested at this temperature.)

Place the specimens in the test machine as described in ASTM C 78. Place thin Teflon strips at the point of contact between the test specimens and the load-applying and load support blocks. While the

beams are being prepared for testing, place an additional support block at midspan to prevent premature sagging of the beams. Remove this support block immediately prior to initiation of load application. Mount the LVDT's on laboratory stands on each side of the beams and attach the LVDT's to the "L"-shaped tabs on the sides of the beams. Connect the LVDT's to the X-Y recorder. Make final adjustments and checks on specimens and test equipment. Apply loading in accordance with CRD-C 21-58, omitting the initial 1000-lb load.

CALCULATIONS

The modulus of rupture (R) is calculated from the equation:

$$R = PL/bd^2 \quad \text{as given in ASTM C78-75}$$

where

R = modulus of rupture, psi

P = maximum applied load, lb

L = span length, in. (18 in.)

b = average width of beam, in.

d = average depth (height) of beam, in.

The modulus of elasticity (E) is calculated from the equation:

$$E = \frac{23PL^3}{1296\Delta I} k \quad \text{as given in CRD-C 21-58}$$

where

E = static Young's modulus of elasticity, psi

P = applied load, lb

L = span length, in. (18 in.)

Δ = deflection of neutral axis, in., under load P

I = moment of inertia $(= \frac{bd^3}{12})$, in.^{4}

b = average width of beam, in.

d = average depth (height) of beam, in.

k = Pickett's correction for shear (third-point loading)

$$\left[1 + \left(\frac{216}{115} + \frac{27}{23}\mu\right)\left(\frac{d}{L}\right)^2\right]$$

The values of E should be calculated without using Pickett's correction for shear (k).

REPORT

The report shall include the following:

a. Gradation of aggregate.

b. Type and properties of bituminous cement.

c. Bituminous concrete mix design properties.

d. Bituminous concrete beam properties.

e. Modulus of rupture.

f. Modulus of elasticity.

END
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